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GROUNDING AND SHIELDING REQUIREMENTS FOR THE RADIATION AND EMP ENVIRONMENTS OF AN UNDERGROUND NUCLEAR TEST

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2860 South Circle
Colorado Springs, Colorado 80906

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20. ABSTRACT (Continued)

and propagation in the Hybla Gold experimental plant is presented in Part II. The conclusions drawn from the environmental predictions logically result in the actions described in Part I. This combined report enables an experimenter to plan and execute such tests with more understanding of the noise sources and how to deal with them successfully.

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PREFACE

In connection with the underground nuclear test (UGT) Hybla Gold, executed November 1, 1977, a study was performed to identify the necessary grounding and shielding considerations and actions to improve the quality of the data obtained. The study consisted of two parts: the first part identified the necessary steps to be taken by experimenters to protect their data channels (coaxial cables or twisted pairs) from the radiation and EMP environmental noise sources; the second part identifies the environmental conditions present as a function of position and time relative to the working point and time of detonation.

This document contains the report of both parts of the study: Part I, Grounding and Shielding Recommendations for Underground Nuclear Tests and Other Simulators of Nuclear Environments, by Larry Scott; and Part II, Analysis of EMP Interference in Hybla Gold Experiments, by Ron Parkinson. The two parts are bound in a single cover to facilitate the planning and executing of such tests by the experimenters.

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PART I

GROUNDING AND SHIELDING RECOMMENDATIONS
FOR UNDERGROUND NUCLEAR TESTS AND
OTHER SIMULATORS OF NUCLEAR ENVIRONMENTS

LARRY SCOTT

1. INTRODUCTION

High-energy environments such as are created in the vicinity of a nuclear explosion have been the concern of a portion of the scientific community for many years. At the request of the Department of Defense, a large number of nuclear explosions have been used to study these environmental effects on the many materials used in military systems, satellites, missiles, avionics, and ground equipment. For the last several years, these experiments have been limited to underground chambers located in a remote area of Nevada to avoid atmospheric detonations. We will be discussing the grounding and shielding for the instrumentation of these underground tests.

Portions of the environment created by a nuclear detonation may be generated by other simulation techniques such as high explosives in large quantities, super-flash x-ray machines, Linacs, and nuclear reactors. These simulation systems can also couple significant amounts of energy into the instrumentation channels, which obscures the desired measurement or data. This report discusses the means of controlling these noise sources, which are very similar to those of a nuclear test.

The philosophy of the grounding and shielding plan (GSP) is to use multiple topological conducting surfaces to provide shielding of the signal conductors from all incidental electromagnetic waves and to provide multiple grounding points located near the energy source to bleed off the unwanted shield currents with a minimum path length. The success of such a system requires careful consideration to achieve a continuous topological surface for each shielding layer, with well constructed connectors and feedthroughs as well as good-quality cable shields and the availability of a true (low-impedance) ground plane or earthing system distributed along the cable plant.

Past experimental data has shown that shielding has been poor at many connectors, with the cable shields not being circumferentially connected and with resultant leakage into the signal path. Also, the long cable runs used in these tests, 3000 to 5000 ft for underground tests (UGT) and 5000 to 7000 ft for high-explosive tests (HET), allow the large shield currents to distribute over the cable bundle (capacitive coupling) and to penetrate the cable shields (inadequate skin depths) to introduce noise into the channel.

The recent execution of Hybla Gold was used to test the above grounding and shielding philosophy, and the associated assumptions regarding earthing in the tunnel environments. All earthing assumptions proved correct, and the good quality of the data (i.e., noise-free) indicates that adequate care was taken regarding the shielding.

A brief listing will be given below of the lessons learned regarding execution of the GSP on Hybla Gold. The rest of the report contains more detailed explanations of these items and some calculations to support the conclusions reached. The appendix contains the Hybla Gold GSP document and a field description. The lessons learned, in approximate priority of importance, are:

1. Special programs, such as the GSP, need to be presented directly to the men that are going to be doing the experiment, not to the supervisory staff or middle-management representatives normally sent to the Project Officers Meetings. For the Hybla Gold GSP, we held six special, separate meetings and still had an education-communication problem with tunnel-field workers; their management did not pass on the technical content of those meetings, and particularly did not pass on the GSP.
2. Cable plant ringing, characterized by the 10- to 100-kHz frequency at about 2-volt levels on signal cable center conductors, evident on many previous tunnel experiments, was not observed on Hybla Gold due to the bleeding off of large noise currents present on the shields of the instrumentation cables. Removing the Compton-type replacement current noise sources from the cable runway prevented the cable plant resonance from being excited. It is very important to use multiple grounding on all cable runs near the working point, to remove the large noise currents flowing on the shields, thus preventing cable plant ringing and feedthrough.
3. Use of grounding pits needs to be improved. Hybla Gold pits used lead shot and interlaced copper wire within an iron box to ground the bare cable shields. This technique yielded satisfactory grounding for the high-frequency shield currents, and an improvement is sought by using copper clad lead shot (BBs) and, perhaps, a liquid (boric acid, plus borax salts for neutrality and magnesium sulphate for conductivity) filler, providing the liquid is contained within the pit.

4. Earthing of the outer conducting shield of the gauge elements near the pipe provides a short return path along a metallic conductor (the outer shield) for the radiation-induced currents and the electromagnetically induced currents resulting from emission of electrons near the gauge element. Node points for earthing of both inner and outer shields are necessary to obtain maximum bleed-off of noise currents. Flexible copper conduit and EMT swedge fittings worked quite well on Hybla Gold.
5. All connectors along the cable run need to be wrapped with copper foil (aluminum foil is not durable enough in a tunnel environment) to provide a circumferential connection from cable shield to connecting bulkhead or extended cable shield running up-hole. A developmental program should be initiated now to find a suitable hardware item to replace this foil-wrap system.
6. Cable tray material was used to provide an outer topological shielding surface for cables near the pipe. This tray must be galvanized or have other corrosion-resistant treatment. Tunnel environments will create a rough oxidized surface for contacts that is nonconducting in a few days when working on unprotected iron materials.
7. Use of DNA-supplied twisted shielded pair (TSP) cable (typically 20 pairs) must be restricted to applications where no appreciable shield currents will be present — i.e., less than 10 amps (estimated). This cable is clearly designed for audio-frequency usage with low-level signals — i.e., telephone cable. DNA is providing a version of this cable with greatly improved outer shield characteristics (braided) for future tunnel-type applications. Proper grounding and connector construction and handling are required to prevent noise sources in this type of cable.
8. Hybla Gold used only concrete pipes that were totally immersed in grout, so that no pipe ringing was observed; however, a vacuum pipe experiment most likely will demonstrate some high-frequency ringing due to the ungrouted pipe length of 700 ft or so, or an approximate 1.5- μ sec ringing period. The grout is very lossy to signals above about 1 MHz, so that the primary

ringing mode is the ungrouted pipe acting as a waveguide or transmission-line structure. The choice of whether to ground to the pipe is dependent on the particulars of the experiment, primarily the frequency range of interest - i.e., milli-, micro-, or nanosecond data.

9. The cables that enter the zero room (A&F) were placed in a separate tray to prevent the large currents expected to flow on their shields from coupling onto gauge or instrumentation cables. After a run of a couple of hundred feet in a grout-filled tray with the shields being grounded in one of the grounding pits, these cables joined the cable bundle.
10. Chicken wire was used in several places in the tunnel configuration to provide a distributed contact to the grout-stemming material or to connect a cable tray to the zero room wall materials.
11. All cable trays were filled with grout as well as being RF-tight, and were well grounded to the surrounding grout, mountain tuff. The grout-filled tray bleeds off the higher frequencies (>1 MHz) from the enclosed cable shields.
12. The mesa trailer park received some attention regarding the GSP, although not as intense as the tunnel environment. Specifically, all cable shields were terminated at the trailer shells, with good copper foil wraps on the connectors which fit into feed-throughs; all extra wire penetrations were removed (cut off) at D-1, such as telephone lines, speaker wires, etc.; instrumentation and utility power systems were isolated from ground so that the trailers floated from ground at shot time or were grounded by means of the signal cable shields only.
13. We strongly recommend the creation of a grounding and shielding quality assurance position on the Test Staff for all underground tests. The responsibility of this position is to coordinate the experimenters' activities, in the laboratory and the field, to assure DNA of the timeliness and quality of the execution of the GSP.

The following sections contain a brief discussion of each of the above items.

2. IMPLEMENTATION BRIEFINGS FOR SPECIAL EXPERIMENTAL PROGRAMS (SUCH AS GSP)

Any special experimental program requiring non-normal practices in the fielding of the experiment necessitates a series of meetings to communicate the program. These special meetings must involve the actual field workers or those directly responsible for the fielding operations, thus circumventing the intra-company communication link. This educational-communication function was the most difficult of the Hybla Gold GSP because we at first relied upon company communication to get the GSP across to experimenters, and it didn't work.

Six special meetings were held to discuss, formulate, and agree upon a GSP. The dates were:

February 24, 1977, NVOO, getting started.

March 17, NVOO, call for proposals of GSP.

April 15, Santa Barbara, Ken Sites and Larry Scott presented the strawman GSP and fielded questions.

May 3, NVOO, agreement reached on recommended GSP, submit to DNA.

June 28-29, NTS, trim GSP to match available budget.

July 14, NVOO, final preparatory meeting.

July 21, Field Command, Albuquerque, all comments in, action items clear, go to field.

After all these meetings, which included all the experimenters as well as the senior EMP community representatives, the field workers still did not understand the GSP, its philosophy, or the actions to implement the GSP. These meetings consisted of presentations, comments, discussions, arguments, even a bit of shouting, on the part of experimenters, the EMP community, DNA advisors, and DNA representatives; they were excellent in light of accomplishing a GSP by consensus.

That so much time and effort were invested in communicating the GSP to the experimenters unsuccessfully was a great surprise to the Hybla Gold staff. Yet, there were numerous examples of fielding activity that indicated a lack of understanding or awareness or appreciation of the GSP. After investigation of the situation, it became clear that the field workers were not informed by their management (who had attended the meetings) of the GSP.

A noteworthy exception to this pattern is Paul DiCarli, SRI, who not only participated in all of the meetings but also was present in the field from the beginning through the end. The SRI installation was executed in a very professional manner and in accord with the GSP. It was apparent that Paul had invested considerable preparation time before coming to the field (i.e., NTS).

As a result of the difficulties experienced during implementation of the Hybla Gold GSP, we strongly recommend that the informative meetings on implementation activities involve the actual field workers, or at a minimum the team foreman, who will be at NTS for the field work. Three such meetings should be adequate, with one at the test site to view the test bed.

A GSP quality assurance position needs to be identified for each nuclear test. This person will be responsible for conducting the above seminars on grounding and shielding, as well as working with the experimenters early in the program to assure DNA that the GSP is being implemented. This QA activity, while being initiated early in the program, must be followed up very diligently in the field. Success of the GSP is quite dependent on consistent treatment of all cables in the cable plant, with the only exceptions being very well justified.

3. SUPPRESSION OF CABLE PLANT RINGING BY MULTIPLE EARTH-GROUNDING

The cable plant, the bundle of a few hundred cables of several cable types that extends for a few thousand feet, has been observed to oscillate or ring on many past nuclear tests as well as other simulator experiments. The model for this oscillator mode consists of the distributed transmission line made up of the cable shields, the insulating jackets, and the tunnel or mountain rock or earth return. The few thousand feet of cable bundle is laying on the dirt of the tunnel, in water in some places, and consequently has a significant capacitive coupling between adjacent cable shields and to earth-ground. The inductive reactance of the cable shields adds to the capacitive coupling to form a low-impedance transmission-line model; this transmission line is unterminated or mismatched, and consequently will ring when excited with an impulse of charge or a noise pulse. The ringing will appear as a damped sinusoid of frequency corresponding to the electrical length of the unterminated transmission line, about 1.5 nsec per foot of cable, or a period of about 100 kHz for a 3000-ft cable plant.

The penetration of this low-frequency signal through the shields of the coaxial cables is very significant over the few-thousand-foot cable run. Even the solid aluminum outer shields (RG-331) have a small transfer impedance (Ref. 1) through the shields over so long a run. The only effective method of excluding this ringing noise from the data channels is to prevent the cable plant from getting excited (carefully balanced signal paths that have high common-mode rejection may also be effective, but are much more expensive).

The cable plant can be prevented from getting excited by keeping the large radiation-produced currents off the cable shields by frequent earth-grounding of the shields, circumferentially, to as good a ground (low-impedance) as can be found in the environment. The relative quality of grounds available necessitates the multiple connection, since some shield current division takes place at each connection and a current of no more than a few amperes at the instrumentation alcove location is desired. This value of a few amperes is determined by the transfer impedance of a connector in the coaxial line; typical values (Ref. 4) are:

$$Z_T = R_0 + j\omega M_{12} ,$$

with

$0.005 < R_0 < 0.05$ for a good connector,

$0.10 < R_0 < 1.0$ for a bad connector,

$2 < M_{12} < 5 \times 10^{-11}$ henries.

The induced noise levels at a connector will be excessive if more than 0.1 volt; hence, shield currents should be kept to less than a few amperes with good connectors.

Note that the earth-ground impedance will create a current divider with the cable shield impedance. Ground pits or nodes must be down to less than 1 ohm to real ground for effective shield current shunting. The cable shield resistance is:

RG-58 0.001 ohm/ft

RG-22B 0.000096 ohm/ft

RG-331 0.00003514 ohm/ft

4. GROUNDING PITS

To facilitate the earth-grounding of the cable shields within the constraints of a circumferential, low-impedance ground, that is inexpensive, a grounding pit was used. The pit consisted of an iron box with open ends and top. As the cables, with about 18 inches of insulating jacket removed, were laid into the iron box, lead shot was poured around the cables, held in by sulfa-set dams at the ends of the box. The Hybla Gold grounding pits also contained a heavy copper wire interlaced through each layer of cable and tied to the iron box, which was connected to a nearby rock bolt — i.e., grounded to the mountain-earth.

The Hybla Gold pit was the source of a great deal of concern due to the oxidation of the lead shot and subsequent high readings of an ohmmeter during checking of grounding resistance. The ohmmeter indicated in excess of 5 ohms between an arbitrary cable shield and the box-ground due to the contact potential of differing materials (Pb, Fe, Cu, Al, etc.) bucking most of the ohmmeter voltage (0.200 volt) used in the measurement. A "megger" was then used, which generates a 10- to 12-volt potential for measuring resistance, and less than 0.5 ohm was indicated cable shield to box and box to tunnel ground. The higher voltage was enough to overcome the contact barrier and yield a more accurate measurement.

A dynamic measurement was made of the shield current division at a grounding pit by the SRI staff, Rob Bly in particular. A large capacitance was charged to several kilovolts (2 μ F to 27 kV) and discharged by means of a spark gap to couple energy onto the shields. A length of RG-213 was stripped of its outer shield and wrapped around the cable bundle before being tied to ground, providing sufficient coupling. This test method was constrained by space requirements to injecting the noise pulse on the cable bundle up-hole of all the grounding pits, so that the current division was between a grounding pit and about 50 ft of cable to another grounding pit, instead of the up-hole cable run of a few thousand feet. The ringing pulse used in this test had a period of a few microseconds and lasted less than 20 μ sec.

Even with the disadvantageous impedance division, the shield currents were reduced by about 17 dB average and an 8-to-1 reduction on braided or solid shielded cables. The two pits at the alcove area and the one at the end of the cable tray provided at least 36 dB of suppression, with about 6 dB at the two gas blocks, or 48 dB suppression of the shield currents. Actually, the current division at the last grounding pit should be based on a comparison of the grounding pit impedance to the up-hole cable bundle impedance, which could yield a better noise current pulse suppression than the indicated 48 dB.

It was considered to fill the grounding pits with a liquid electrolyte such as boric acid plus borax for a neutral solution (i.e., pH of 6 to 7) and magnesium sulphate (Epsom salt) to adjust conductivity. The pits of Hybla Gold were located in such a way that the liquid would run along the cables for a good portion of the cable length. Concern for potential shorting of the cables through dielectric pinholes stopped this considered action. Future pits should be constructed so as to limit any liquid to the location of the grounding pits — i.e., lower the pits to make them the lowest locality in the cable run. We also recommend using copper-clad lead shot or BBs as used in "Daisy" air rifles. The copper plating should greatly enhance the conductivity.

5. FREQUENT EARTHING OF OUTER AND INNER SHIELDS NEAR THE PIPE OR GAUGE ELEMENT

The object of grounding the shields near the gauge elements or pipe is to remove the radiation-induced shield currents as close as possible to the point of origin so that the currents travel a minimal distance along the cable shields. This in turn minimizes the noise feedthrough to the center conductor of the cable and prevents the cable plant from ringing.

Both the inner and outer shields were earth-grounded at multiple points in Hybla Gold, assuming that the earth-ground node points were sinks of noise energy, not sources. This assumption was borne out by the Hybla Gold test-bed results.

Mountain rock or grout ground proved to bleed currents off the cable and not add to the noise, either by injecting at the node or by providing a ground loop. As long as the assumed ground is a significantly lower impedance than the remainder of the loop created, a bleeding off of energy will occur, not increased noise. Again, the results of Hybla Gold demonstrate the validity of this assumption about low-impedance earth grounds in the tunnel.

The usefulness of grounding both inner and outer shields at common node points is demonstrated by EMI shielding practice (Ref. 2). Any shield current on the inner shield surface (due to emission currents) needs to be bled off to ground to avoid leaking through to the center conductor.

Use of brass or galvanized iron pipe fittings is a must in the tunnel environment for materials used in making electrical contact by pressure alone — i.e., pipe nipples and jam nuts.

6. CONNECTOR QUALITY ASSURANCE

In accordance with the criteria for a good continuous conducting topological surface which encloses the center conductor, the treatment of the shield of a coaxial cable is very critical and deserves special attention (Ref. 2). For the cables of Hybla Gold, a foil wrap was used to secure the connection from the cable shield to the connector shell or bulkhead conducting plane (as in the gas block scheme). The insulating outer jacket is stripped back and the foil is then wrapped around the cable, being secured with conducting epoxy and then a pipe clamp. The foil was then carried to the protruding shell surrounding the connector body, where again a circumferential connection was made with conducting epoxy and a pipe clamp. A similar technique is to be used for joining two cables with connectors or at splices. Care must be exercised to waterproof the complete assembly, to prevent deterioration of cable impedance or conductivity due to moisture effects (Appendix A). Also, it is recommended that copper foil be used rather than aluminum due to potential corrosion of aluminum in the grout/water environment.

Any gaps in the shielding surface along the cable may allow shield currents to leak into the signal path, causing a decrease in signal-to-noise ratio.

A more standard, earlier-to-use hardware item that provides this circumferential contact needs to be developed. A brass or protected aluminum casting that is easily used is required to simplify and improve this connector difficulty.

Elimination of the gas block bulkhead is also worth considering, if a gas-blocking cable can be used to replace the connector interface of the bulkhead. Keeping connectors out of the grout would eliminate a great source of cable loss and data channel loss (at \$20,000 to \$30,000 per channel!).

7. USE OF CONDUCTING MATERIALS FOR A CABLE TRAY NEAR THE PIPE

The outer topological surface used to shield gauge cables near the experimental pipe run was a cable tray. The tray was constructed of common sheet steel with a flanged upper lip to which a lid was attached with RF gasketing. This conducting enclosure of the gauge cables was not galvanized or treated to prevent oxidation, and in the tunnel environment it became rusted in just a few days. The cable feedthroughs were attached to the cable tray with a jam nut and washer which relied on a clean surface for good electrical contact, not manifested in the rusty material. For Hybla Gold, a great deal of extra labor was required to clean off these working surfaces and seal them with conducting epoxy to ensure a good electrical contact. We recommend using a galvanized material for the cable tray.

The feedthroughs were also the location of a grounding node for the inner and outer cable shields of the gauge cables. The mechanical arrangement was not particularly satisfactory. For most fittings, a bit of foil or braid was simply jammed into the space between the bare cable shield and the pipe nipple used as a feedthrough. Sandia designed a brass fitting to accomplish this electrical contacting and obtained good results. This fitting or a similar one should be considered for future applications.

8. DNA-SUPPLIED TSP CABLE

This cable has become the object of a great deal of study, still on-going, by DNA and various experimenters. The basic difficulty is the construction of the cable to meet low-frequency audio shielding requirements and its subsequent application in the high-current, high-frequency noise environment of the nuclear testing world. Shielding effectiveness at high frequencies appears to be lacking, perhaps even causing arcing and contributing noise. Experimental determination is being made of the shielding effectiveness of this cable for nuclear simulation testing.

The basic shielding of this cable is an aluminized mylar foil spirally wrapped along the cable bundle — a group of 20 or so twisted pairs. Each pair is wrapped with such a foil, also enclosing a bare ground wire to provide a low-inductance ground. The use of a foil shield seems adequate to protect the individual twisted pairs from crosstalk — i.e., capacitive coupling between pairs; the twist gives magnetic protection.

The spiral foil outer shield may produce arcing between wraps if the current on the foil exceeds a few tens of amperes at a few megahertz. The arcing would then couple into the enclosed pairs and deteriorate the signal quality. For example, if inductance of one wrap of the foil is about 10 nH and the current is about 50 amps at 100 MHz (3.5 nsec rise time), a potential of over 300 volts is present between the overlapping layers of the aluminized mylar, perhaps enough to cause arcing.

This type of cable can be used; however, the application needs to be restricted to areas of low shield currents (<10 amps) and low-frequency noise environments. The drain wire, a bare conductor running the length of the cable just under the foil, needs to be grounded at frequent intervals along the cable to suppress buildup of noise currents. However, DNA is now replacing the foil outer shield with a braid shield (similar to RG-213), single- or double-layered as cost allows.

9. GROUNDING TO THE EXPERIMENTAL PIPE

The experimental pipes on Hybla Gold were made of concrete and were immersed in grout; consequently, no ringing was observed since no potential oscillators were present. The closest approximation to a pipe was the cable tray, which was buried in grout and had a grout filling. Due to the losses in the grout, especially above 10 MHz, no oscillation could be sustained in the cable tray structures, and none was observed.

In a vacuum pipe shot, a portion of the pipe is buried in grout and will not sustain external oscillations. The portion of pipe outside the grout is essentially a transmission-line structure and may oscillate at a frequency corresponding to a wavelength equal to twice the free-pipe length - i.e., for 700 ft, about 1.4 μ sec. Several oscillations may be necessary for the signal to dampen out (i.e., about 10 periods), depending on the lossy experimental structures attached to the pipe. Some trapped energy may be in the waveguide mode of the pipe which will ring for longer time periods.

The decision to ground a sensor system to the pipe or not depends on the sensitivity of the sensor circuit signal-conditioning electronics to the potential ringing noise. A low-frequency-type strain gauge sensor may be more tolerant than a high-frequency pressure measurement. Due to the potential oscillations on the pipe, it is best to ground to rock bolts or earth-grounds just off the pipe but still near the front end (see Husky Pup Add-On Experimental Results, or Dining Car POR 6892, 1977).

10. PARTICULAR TREATMENT FOR A&F CABLES

The shielded cables running into the zero room were kept separate from the instrumentation cables. These cables are not needed after detonation, so their noise suppression is not a problem. The large shield currents predicted on these cables, due to proximity to the device, make these cables a threat to the cable plant, since the large shield currents can couple to other cables in the bundle and/or cause cable plant ringing.

To prevent these large anticipated currents from reaching the instrumentation cables, a separate cable tray was used which totally enclosed these cables. This conduit was also grout-filled to bleed off the high-frequency Compton currents or noise on the cable shields. After running the length of the pipes in the auxiliary drift (approximately 300 ft), the A&F cables were taken through a grounding pit, where they joined the cable bundle.

This handling of the A&F cables or others similar, to remove the large noise currents from the shields before they are allowed to mix with the instrumentation cables, gave good results on Hybla Gold.

The model of interest here is to consider the cable plant a tank circuit, parallel R, L, and C elements. The Compton current generator acts to provide an impulse of current or a charge deposition lasting several nanoseconds onto the capacitance, initiating a ringing response. Removing the high-frequency impulse of the radiation-induced shield currents will prevent the cable plant from ringing, since the oscillatory mode will not be excited if the current pulse is shunted to ground. By reducing the energy of this impulse of noise current, the oscillation can be suppressed, or simply not initiated (Ref. 2).

11. CHICKEN-WIRE MESH FOR DISTRIBUTED GROUNDING AND LOW-INDUCTIVE CONNECTIONS

In those placed within the Hybla Gold GSP where different large conductors need to be connected, such as cable trays to the zero room wall, a low-inductance distributive connection was made with chicken-wire mesh (galvanized-dipped after weaving). This material was also used to form a distributed connection to the grout near the end of the cable trays to provide a ground connection for the grounding pits.

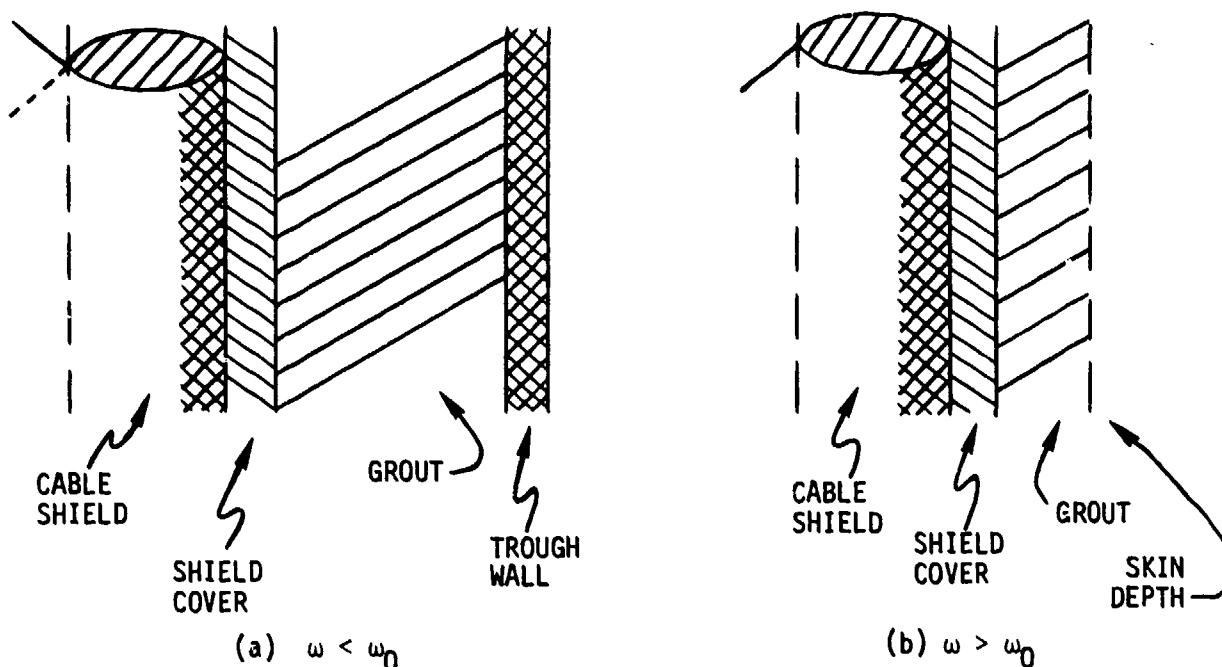
12. CABLE TRAYS, GROUT-FILLED

To provide a lossy medium for the high-frequency noise currents on the cable shields, the cable tray-conduits were filled with grout. An analysis was performed of the grout-filled tray containing a jacketed conductor as a transmission-line structure. Excerpts from that analysis are included here. Grout conductivity was measured at Dining Car [$0.02 \text{ (ohm-m)}^{-1}$] and used in this analysis; however, the results are not very sensitive to this value.

We conclude that attenuation of noise currents on the shields below 10^6 Hz is small (0.012 neper/m) but increases rapidly with increasing frequency above 10^6 Hz; i.e., at 10^7 Hz attenuation is 0.54 neper/m. A neper is equal to 8.686 dB, so the attenuation in 100 m of conduit is 10.4 dB for a 10^6 Hz shield current and about 469 dB for a 10^7 Hz component. The Compton components we are concerned with in this experiment are predominantly above the 10^7 Hz frequency.

Model Parameters

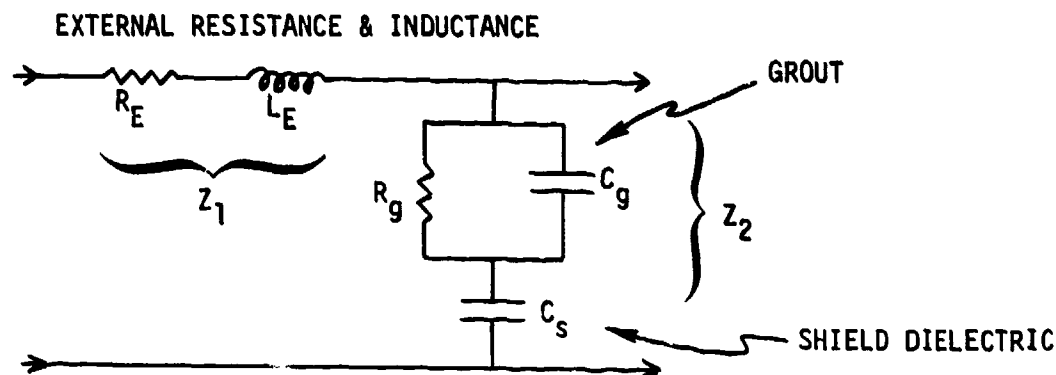
We are interested in losses introduced by purposely grouting cables in a metal trough. We will consider two models; if ω_0 is the frequency at which skin depth δ in grout equals the trough dimensions, the models for the transmission line are:



We will show typical numbers for both cases:

$$2\pi f_0 = \omega_0 = \frac{2}{\mu\sigma\delta^2}, \quad f_0 = 316.6 \text{ MHz}.$$

For all frequencies, our model will be that of one length of transmission line:



and the propagation constant is just

$$\alpha + j\beta = \sqrt{Z_1/Z_2},$$

where α is the attenuation.

All we have to do is algebra for the above circuit:

$$Z_1 = j\omega L_E + R_E,$$

$$Z_2 = \frac{1}{j\omega C_s} + \left[\frac{1}{R_g} + j\omega C_g \right]^{-1},$$

finding

$$\alpha + j\beta = \sqrt{(j\omega L_E + R_E) j\omega C_s} \left[\frac{1 + j\omega C_g R_g}{1 + j\omega(C_g R_g + C_s R_g)} \right]^{1/2}.$$

We can evaluate the above expressions in $\delta_g \leq D_g$ and $\delta_g \geq D_g$ limits in a straightforward manner (D = dimensions of grout trough). See program.

Attenuation rates and wave numbers obtained for the assumed "typical" parameters are tabulated in Table 1. The tabulation shows α and β , where the signal amplitude propagating down the cable sheath is proportional to

$$A(x) = \exp[\alpha(\omega) + j\beta(\omega)] x,$$

as a function of distance. It appears that attenuations are only about 0.012/m at $f = 10^6$ Hz, but increase to 0.54/m at 10^7 Hz. The theory in the neighborhood of 300 MHz is not extremely good, since skin depth and cable trough dimensions are comparable there. The predictions at still higher frequencies are presumably better again.

Compton currents produced in the cable shield by the gamma flash will have very-high-frequency components, $> 5 \times 10^7$ Hz, so that the model is fine for the region of interest.

PROGRAM DIDL

COMPLEX CI, PPH, CO

DATA TWOP1 /6.28318/

DATA XMUO, EPSO /1.257E-6, 8.854E-12/

DATA EPSP, EPSG, SIGMAG /2., 2., .02/
DATA RS, DRP, DRG /.01, .001, .15/

CI = (0., 1.)
IO 9 IDEC = 3, 9
IO 8 IPHR = 1, 9, 2
PHR = FLOAT((10++IDEC)+IPHR)
OMEGA = TWOP1+PHR
CO = CI+OMEGA
SD = SQRT(2./(XMUO+SIGMAG+OMEGA))
IF(SD .GT. DRG) SD = DRG + 1.E-5
XL = (XMUO/TWOP1)+ALOG((RS + DRP + SD)/RS)
XR = 1./(SIGMAG+((RS+DRP+SD)**2 - (RS+DRP)**2))
IF(SD .GE. DRG) XR = 0.
CP = TWOP1+EPSP+EPSO/ALOG((RS + DRP)/RS)
CG = TWOP1+EPSG+EPSO/ALOG((RS + DRP + SD)/(RS + DRP))
RG = EPSG+EPSO/(CG+SIGMAG)
PPH = CSQRT(CO+CP+(CO+XL + XR))+CSQRT((1. + CO+CG+RG)
/(1. + CO+RG+(CP + CG))
TYPE 1, IDEC, IPHR, PPH

CONTINUE

CONTINUE

FORMAT(1H , 215, 2E15.3)

CALL EXIT

END

Table 1

KXCT DIDL EXECUTION

		$\alpha \text{ (m}^{-1}\text{)}$	$\beta \text{ (m}^{-1}\text{)}$
3	1	-0.125E-07	-0.160E-03
3	3	-0.113E-06	-0.480E-03
3	5	-0.313E-06	-0.800E-03
3	7 x 10 ³	-0.614E-06	-0.112E-02
3	9	-0.102E-05	-0.144E-02
4	1	-0.125E-05	-0.160E-02
4	3	-0.113E-04	-0.480E-02
4	5	-0.313E-04	-0.800E-02
4	7	-0.614E-04	-0.112E-01
4	9	-0.102E-03	-0.144E-01
5	1	-0.125E-03	-0.160E-01
5	3	-0.113E-02	-0.480E-01
5	5	-0.312E-02	-0.798E-01
5	7 x 10 ⁵	-0.609E-02	-0.112E+00
5	9	-0.100E-01	-0.143E+00
6	1	-0.123E-01	-0.159E+00
6	3	-0.985E-01	-0.445E+00
6	5	-0.226E+00	-0.668E+00
6	7	-0.359E+00	-0.838E+00
6	9	-0.481E+00	-0.971E+00
7	1	-0.537E+00	-0.103E+01
7	3	-0.123E+01	-0.179E+01
7	5	-0.158E+01	-0.237E+01
7	7 x 10 ⁷	-0.181E+01	-0.292E+01
7	9	-0.198E+01	-0.346E+01
8	1	-0.204E+01	-0.373E+01
8	3	-0.246E+01	-0.928E+01
8	5	-0.253E+01	-0.151E+01
8	7	-0.124E+02	-0.219E+02
8	9	-0.154E+02	-0.284E+02
9	1	-0.169E+02	-0.317E+02
9	3	-0.486E+02	-0.988E+02
9	5	-0.817E+02	-0.167E+03
9	7	-0.115E+03	-0.235E+03
9	9	-0.149E+03	-0.303E+03

13. THE MESA TRAILER PARK CONSIDERATIONS

The Hybla Gold GSP focused upon the downhole tunnel environment, with the understanding that by containing the prompt radiation-induced emission currents, quickly bleeding them off the cables, and tightly shielding the signal conductors, the worst noise sources would be eliminated. Consequently, the actions taken at the mesa were of a lower priority.

Most significant of the mesa activities was to not produce ground loops to reduce the potential pickup from atmospheric noise sources, lightning, TV-radio frequencies, etc. To accomplish this configuration, the trailers were mounted on insulating plates; instrumentation power provided to the trailers was isolated by use of motor generators or diesel power. The utility power was supplied via isolation transformers or diesel generators. The trailer shell, instrument, and utility power were floated from ground on D-1 by removing the green wire neutral and throwing the isolation switch; feedthrough isolation transformers were provided for the coaxial cable signals from the alpha sled (FIDU) to each trailer. The only ground for the DNA trailer shells was that provided by the signal cable shields, which were connected to ground at the bottom of the drill casing from the mesa, at the overburden plug.

At the feedthroughs in the trailer shell, all connectors were wrapped with foil, copper or aluminum, to provide a good circumferential connection to the shield for bleeding off any noise currents. The foil was held in place by a cable tie wrap (plastic ribbon).

The DNA TSP cable had its drain wire grounded at the entry point to the trailer shell. Connectors for the DNA TSP were not wrapped due to lack of a good high-frequency shield material for connection.

All openings in the trailer shells were blocked or closed at D-1, and pipes and holes were stuffed with wadded-up foil or were sealed with conducting tape. All cables — power, telephone speaker, etc. — were removed at D-1, cut off if necessary to eliminate this leakage path for noise signals into the trailers.

The smoke-fire alarm system needed special attention. This system had power lines and signal lines penetrating the trailer shells. The system can switch to battery power and run for about 48 hours. The system detects both

smoke and high temperatures. Since the trailers have a high-temperature monitor built in, the redundancy indicated that removal of the units at D-1 was the best solution to eliminate power and signal cable penetrations.

Since the signal cables from these units lay on the mesa, about 50 ft of cable running to a transmitter unit, the antenna characteristics of this short cable are manageable. If the system were re-engineered to consider the noise immunity requirements, removal of the units at D-1 would not be necessary; an RFI filter or other isolation circuitry could be used for protection.

At this time, however, removal appears to be the best solution, or removal of the cables which still allows a chemical fire retardant to be released on alarm (which is battery-powered).

14. SOME GENERAL COMMENTS ON INSTRUMENTATION FOR HYBLA GOLD

To minimize the effects of prompt radiation-produced emission currents with the sensor system, a differentially balanced system is highly recommended. By using a balanced system, the radiation currents become a common-mode signal which may be rejected by a balun-type transformer or other suitable circuit. This transformer system works well in the tunnel environment due to the robust quality of a transformer as compared to a radiation-sensitive amplifier. The two conductors of the balanced front end may be enclosed in a single shield, as in RG-22B, or can make use of two separate RG-213 cables, all enclosed in a grounded conduit.

At the alcove, which is a relatively radiation-free environment (a few rads), the electronics of the signal-conditioning circuit will be located. This electronics must be enclosed in RF-tight enclosures, good sealed boxes with RF gaskets. Power supplies must be filtered at the incoming power side, with the filter located outside the RF enclosure for isolation of noise on the power lines. The power distribution within the alcove needs to be well shielded, placed within conduits as possible.

Care must be taken with water-tight enclosures for electronics that are placed in the grout environment, due to the high water content of the grout. Hybla Gold had a bad experience when filling an enclosure with RTV (room-temperature curing rubber) to provide moisture control. It appears that a heating problem developed; the RTV acts as an overcoat for active devices such as transistors or integrated circuits, raising the temperature very significantly. Failure of circuits, in grout, was experienced, with an 18- to 20-second operation time between a 2- to 4-hour off time to cool. In addition, the acid produced during the cure of the RTV attacked the copper printed-circuit conductors and caused failure.

At the gas block, only the solid shield cables (RG-331, 333) were wrapped with foil to provide a good shield current bleed path to ground around the connector. Signals on the braided shielded cables were lower-frequency and were grounded a few feet on either side of the gas block by the grounding pits. Also, the long lengths of braided shield have a transfer impedance that is much higher than the connectors, so they are not significant on these channels.

All cable shields were grounded at the bottom of the up-hole drill casing, at the unistrut support members next to the overburden plug (OBP). No additional grounding was done on the mesa due to a limit in the funding.

The use of multiple-point grounding, by means of grounding pits, gas block bulkheads that are conducting, ground connections to the OBP unistrut, and alcove treatments, accomplished the goals of the Hybla Gold GSP. Implementation of the GSP was closely watched over by a GSP quality assurance (QA) man, Larry Scott, at the test site and, to some extent, before hand in the laboratories. The QA function is very necessary for proper implementation of the GSP. Frequent on-site interaction with the experimenters proved to be effective. However, interactions of the QA person at the experimenter's laboratory facility very early in the preparations for the shot are the most effective.

15. CONCLUSIONS

Based upon the high quality of the data obtained in Hybla Gold, particularly the absence of cable plant ringing and the other noise sources usually observed, we conclude that the GSP was successful. Basic assumptions demonstrated by this experiment are that tunnel earth is a good useful ground, which can remove noise currents from the cable shields, that cable plant ringing can be suppressed by removing the excitation of the prompt radiation-induced noise currents, and that multiple shielding of the signal conductors provides adequate protection to observe millivolt-level signals in the micro-second time range.

In future nuclear simulation tests, both underground and in super-flash x-ray or reactor-type surface simulators, as well as high explosives testing, the above considerations for reducing noise in the data channels will be effective. Implementation of these innovations will be achieved according to the level of understanding and acceptance by the DNA staff and the experimenters, as well as according to time and budget restraints. GSP seminars and a full-time GSP QA man will really help overcome these difficulties. Diablo Hawk will be able to make use of many of these innovations, although the timing and magnitude of that experiment preclude a full GSP.

Particularly, Diablo Hawk may be considered in three portions: the EMP add-on, structures experiments, and radiation experiments. The EMP add-on is using the full GSP approach (similar to Hybla Gold) to provide full protection. The structure and radiation experiments are using the multiple cable plant grounding scheme, with ground pits, and close-in grounding at all experiments (with experimenters' cooperation).

It is my hope that the next underground test, Miner's Iron, will include a GSP from the beginning, requiring these considerations to be included by the experimenters from the early proposal phase. The GSP quality assurance person can then be engaged from early in the program to ensure the proper implementation, in the laboratory and in the field, of the GSP.

PART II

ANALYSIS OF EMP INTERFERENCE
IN HYBLA GOLD EXPERIMENTS

RON PARKINSON

1. INTRODUCTION

1.1 INTERFERENCE PHENOMENA OF CONCERN

The primary orientation of the Hybla Gold experimental measurement was toward study of a variety of shock phenomena. EMP interference with the measurements was an important concern, and a substantial effort went into understanding and minimizing EMP problems. The total effort included analysis of the appropriate environment and coupling phenomenology, hardening of "front-end" elements of the individual experiments, and further hardening of the "downstream" instrumentation system: cabling, alcove electronics, grounding, and uphole instrumentation vans.

In general, sources of radiation/EM interference that were considered included internal signals driven more or less directly (by gamma radiation penetrating the gauges themselves) and interference driven by external shield currents that couple to signal conductors through secondary paths, such as shielding defects. External/internal coupling can be important, of course, both near the experiment front end, where the shield currents originate, and also downstream in alcove and cable-plant areas where many coupling and cross-coupling interface hazards (such as signal-conditioning equipment, junction boxes, and bulkhead feedthroughs) can be found. The analysis to follow will concentrate upon front-end coupling phenomena, but results will be relevant to some aspects of the downstream problem, and these will also be briefly discussed.

The time scales of interest in the majority of measurements were late in comparison to gamma-ray and fast-neutron arrival times: radiation dose rates at shock arrival time at some given point in the 3-foot pipe were typically 4 to 5 orders of magnitude below the peak rate seen at the same point, so that survival of gauges in the early-time radiation/EMP environment and minimization of the later measurement-time noise were the two aspects of most concern. Some EMP measurements per se were performed, however, to scale interference levels and monitor the effectiveness of hardening measures.

It is important to note that a number of interference sources that are more difficult and uncertain to evaluate than direct gamma and internal EMP fields may also be significant. The former category includes breakdown noise, noise due to structural motion and/or failure of structural elements, a number of plasma effects, including MHD-associated currents and photo- and thermo-electric phenomena, and departures from the idealized geometries assumed for the environment calculations. Current localizations on cables, pipes, mesh at the tunnel wall, and so on can, of course, be sources of more intense interference than the free-field environment. The environment calculations per se, therefore, simply scale probable interference levels in a manner that will be made more clear and, it is to be hoped, more useful, below.

1.2 EXPERIMENTAL CONFIGURATION

It is inappropriate to discuss the experiment in great detail here, but some description of EMP-relevant aspects should be considered for completeness. Briefly, gauges associated with the individual measurements were disposed at many points along sets of air-filled concrete pipes in two separate drifts. The main drift (about 300 feet long) contained two pipes: one ~3 feet in diameter, and a second 6 inches in diameter. The second drift (~200 feet long) contained three 1-foot pipes. The pipes were situated in the drift cross sections as indicated in Figure 1. None of the pipes looked directly at the working point, and both drifts were completely grouted before the shot, so that the nuclear radiation environment reaching individual experiments from the working point was fairly complicated from the scattering and transport standpoint. Conducting structures embedded in the grout included the gauges and their associated electrical conduits extending (roughly perpendicularly) from the pipes to a steel cable tray, the steel cable trays themselves, running (one in each drift, as shown in Figure 1) the length of the drift, and miscellaneous structural metal, including steel mesh at the tunnel wall, and some framing around the pipes. Some signal cables were also run longitudinally at several points both inside and outside the pipe's cross section, but usually near the pipe wall. Some steel pipe and additional structure used in diagnostic measurements are shown in Figure 1, indicated there as a LASL measurement.

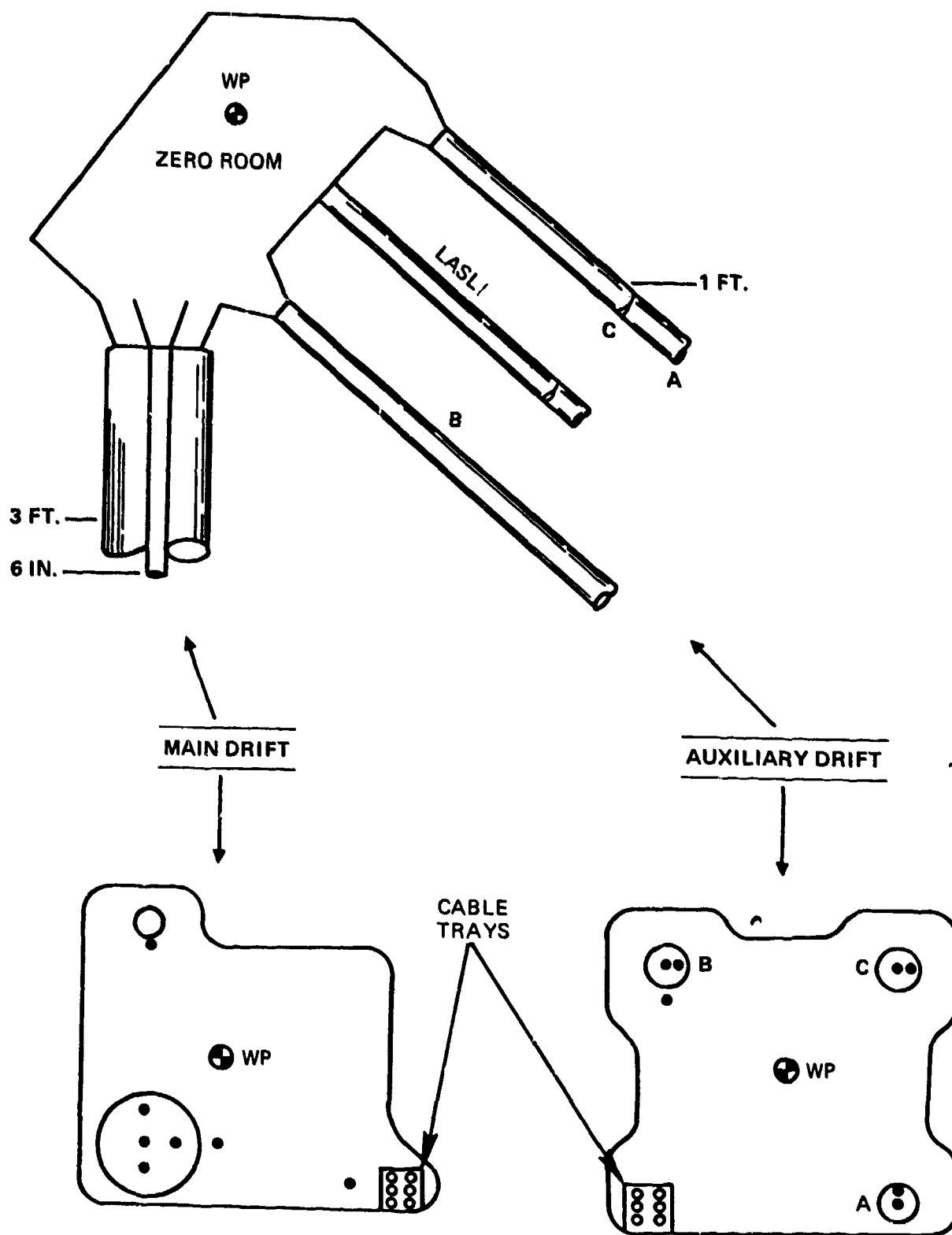


Figure 1. Sketch of drift and pipe configuration

The gauges used in individual measurements were typically housed in shield cases much longer (1-2 m) than their diameter (5-20 cm); the gauges were usually aimed at the center of the pipe and perpendicular to its axis, with the front of the gauge near either the inside or the outside of the pipe wall. (Exceptions included a pipe-expansion measurement utilizing a large-diameter coil girdling the 3-foot pipe, the longitudinal slifer/TDR cables mentioned above, and some rather large debris-measurement arrays located at the ends of the pipes.)

Before proceeding to the quantitative details of the close-in EMP environment and coupling problem, we will briefly describe an experimental configuration of typical interest. Figure 2 shows (not to scale) a schematic drawing in which the important EMP phenomena are indicated. The gauge sensor element is shown (in an idealized form) providing a balanced signal through a continuous internal shield to alcove or other downstream electronics. The internal shield was, in fact, not present in all experimental configurations, although its use, where possible, was considered extremely helpful. Continuous external shielding is also provided first by a gauge outer casing, then by a conduit from gauge casing to cable tray, and finally by a fully closed, grout-filled cable tray that gathers cables from all experiments for the length of the pipe drift. Exterior shield currents are driven by the local gamma-ray/EMP environment at the gauge, and also by the free-field environment that couples to extended structures in the vicinity of the pipe. Internal currents are driven by the gamma-ray and electromagnetic environments close to the end of the gauge (where the radiation environment is most intense), but also by leakage due to shielding defects which may provide coupling between primary shields, secondary shields, and signal conductors in the cable core. The amount of leakage and its significance is, of course, strongly influenced by such practical matters as the quality of the joints between shield elements and the common-mode rejection properties of the signal processing circuitry. External and internal shields are tied together at the points indicated, to localize spurious shield currents to the region in which they are generated. The grout surrounding the gauges and filling the cable tray is a lossy electromagnetic medium and, therefore, also effective at high frequencies in bleeding off high-frequency currents from shields lodged in it.

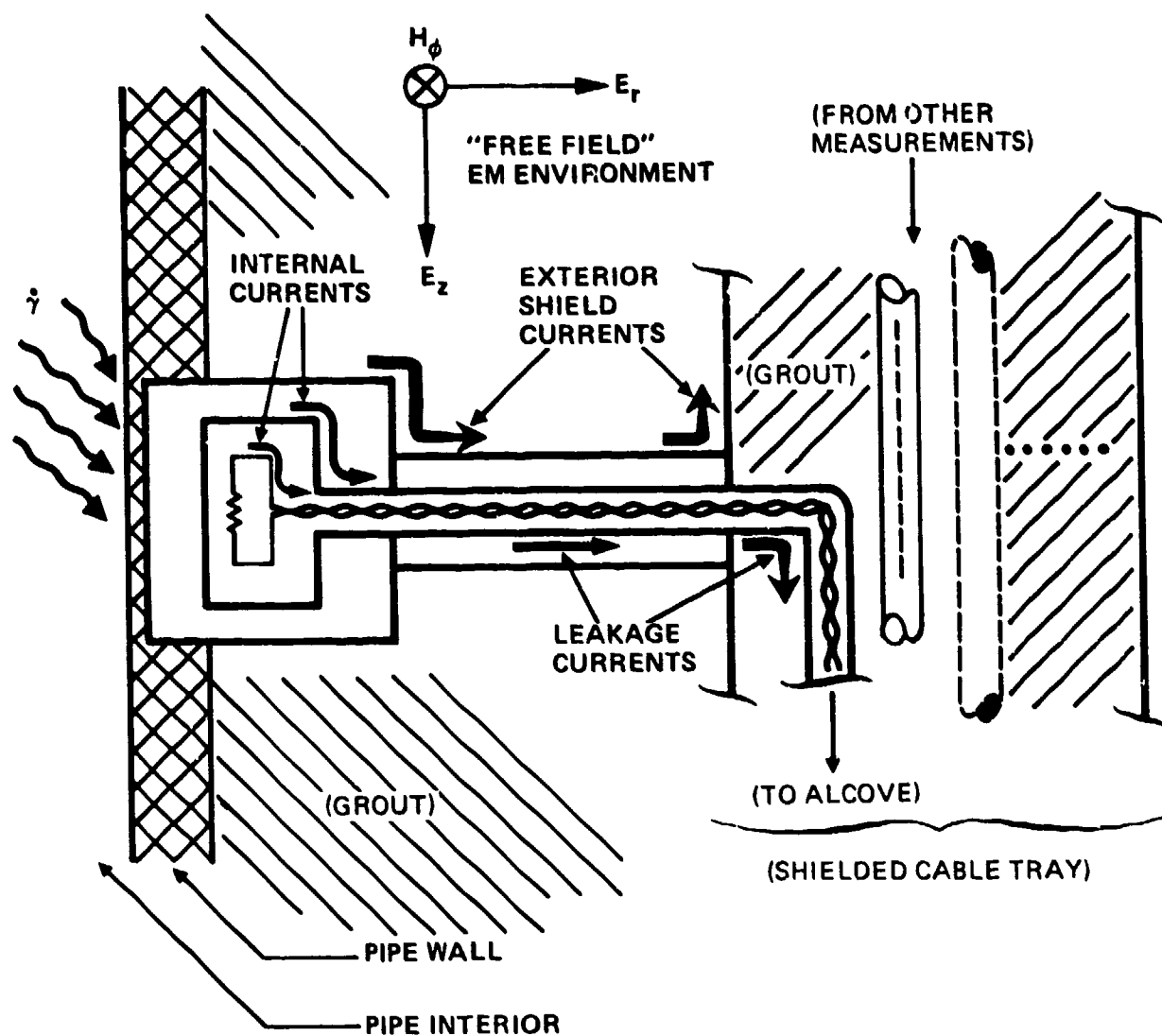


Figure 2. Schematic of ideal gauge shielding geometry in relation to pipe and cable tray

As it is discussed in the following, the environment and coupling analysis will be concerned with all the phenomena noted in the above paragraph — directly driven internal signals, shield currents associated with local fields, and currents due to the free-field environment. We will also consider briefly expected damping and coupling effects. The complex and important aspects of hardening signal-processing circuitry and other downstream parts of the experiment, as well as documentation of some practical aspects of the front-end hardening, have been covered in Part I.

2. ENVIRONMENT: GENERAL CONSIDERATIONS

2.1 GAMMA-RAY ENVIRONMENT

The gamma-ray environment creates both direct and indirect effects through electron currents driven by Compton scattering. The separation is foggy, but one may at least consider extremes: cable replacement currents are a direct-drive phenomenon in which electron transport, rather than the EM field per se, dominates. Typical radiation-induced cable core currents are about 10^{-12} to 10^{-11} amp/m of exposure and per rad/sec of dose rate (Ref. 5). Indirect phenomena typically involve EM coupling in which fields (built up by Compton current flow in an extended medium) are more significant. Typical Compton current densities are about 2×10^{-8} (amp/m²)/(rad/sec) for both air and concrete.

The nuclear radiation environment for experiments situated along the concrete pipes used in Hybla Gold was complicated because of the indirect path from working point to experiment. Nuclear reactions and scattering in the zero-room filler and walls, further complicated by intense heating and hydrodynamic flow, must be considered in some detail for adequate estimates of the down-the-pipe environment. Such calculations have been carried out by W. H. Scott at SAI (refs. 6,7). His results included time-dependent dose rates as a function of displacement down the pipe axis and estimates of dose rate attenuation with radial displacement from the pipe axis. Similar calculations have been informally reported by R. Streetman of LASL. The latter results are apparently in good agreement with Scott's at early times, with some disagreement at later times. At 50 m range in the 3-foot pipe, for example, the LASL dose rate results are about two to three times higher in the 100- μ sec to 1-msec time regime. However, uncertainties in the calculations (principally heating and flow in and near the zero room) could lead to as much as order-of-magnitude uncertainties in the expected environments.

Referring the reader to appropriate reports (Refs. 6,7) for detailed discussion and results, we will attempt to summarize the dose-rate curves as follows.

The time-dependent dose rates expected at the pipe center show a double-humped structure, the first corresponding to early-time gamma-ray output of the zero room and the later one to arrival of neutrons at the observation point in the pipe. The separation of the humps increases with range down the pipe, as one would expect. At about 10 μ sec, dose rates have dropped by two or three orders of magnitude from their early-time peak values, and drop more slowly thereafter, about another order of magnitude between 10^{-5} and 10^{-3} sec. The gamma-ray dose rate in the air-filled portion of the pipe is approximately independent of radius at a given range, but drops rapidly with depth into the grout beyond the inner pipe wall. The initial drop is about a factor of 40 in the first 10 cm of grout, with subsequent drops of about one e-fold for every additional 11 cm of depth.

Dose rates at pipe center are summarized in Table 2-1, which shows typical early- and late-time radiation environments as a function of range.

Table 2. Summary of Radiation Environments

Radius (in)	$\dot{\gamma}$ (rad/sec)		
	Prompt	Fast Neutrons	$\sim 100 \mu$ sec
3	1.5×10^{13}	8×10^{12}	3×10^9
10	5×10^{11}	2×10^{11}	1×10^9
30	3×10^{10}	1×10^{10}	3×10^7
50	1.5×10^{10}	3×10^9	2×10^7
80	3×10^9	8×10^8	7×10^6

2.2 APPLICABLE EM PHENOMENOLOGY

A detailed discussion of the phenomenology and methods of solution for the relevant EM field and coupling problems is appropriate here. It may be useful to summarize the approach, however, together with some comments about peculiarities of the situation of interest.

The general approach used involved finding solutions to Maxwell's equations by numerical methods. The detailed statement of the problem included the boundary conditions (represented by conducting surfaces) and driving

("source") terms representing radiation-driven Compton currents (e.g., in air and grout media) and closely associated time-varying conductivities. Outputs of the calculations included electromagnetic fields, as a function of position and time, and currents (as implied by nearby magnetic fields) on conducting boundaries. Various geometric and physical idealizations are employed to make the problem a reasonable one; this approach is particularly appropriate for the present interference-oriented considerations. Besides the field-calculational aspects of the problem, auxiliary physical models for driven Compton currents and conductivity were required.

Compton currents were found by a simple scaling from gamma-ray dose rate in both air and dielectric media, and field self-consistency effects on the Compton electron trajectories were not included — probably acceptable because the assumption is conservative from the present standpoint.* Directionality of the driven currents (not obtained in the radiation transport calculations described above) was modeled by ad hoc but plausible assumptions. While it has been shown that detailed characteristics of the expected fields are sensitive to the current model employed, general characteristics are again of most interest here. The Compton electron range (in air) is large compared to typical pipe dimensions, but a detailed consideration of electron production and transport in the pipe was not possible in the time allowed for analysis.

Conductivity calculations were also quite conventional. The air conductivity was modeled by a lumped-species treatment with conventional parametrizations for rate and mobility constants. Dielectric materials were considered to display a linear relation between conductivity enhancement and local dose rate; typical parameters for a few materials of interest are shown in Table 3. It is to be emphasized that the figures shown are rough, because of often important temperature and dose-rate dependencies, and are intended to be indicative of the range of enhancement coefficients.

*Note added in proof: It was pointed out by L. Schlessinger that self-consistent effects are more important — particularly for E-fields normal to the direction of the gamma flux — than implied by this statement. Effects on the magnetic field and subsurface E-fields are probably smaller, however.

Table 3. Some Approximate Coefficients for
Radiation-Induced Conductivity*

Material	$\Delta\sigma/\dot{\gamma}$ (mho/cm)/(rad/sec)
Epoxy	7×10^{-20}
Teflon	2×10^{-18}
Glass	1×10^{-17}
SiO ₂	2×10^{-16}
Concrete	2×10^{-16}
Sapphire	7×10^{-14}

*See, for example, T. M. Flanagan and R. H. Stahl, "IRT Support of Husky Pup Granite Block Experiment," IRT report of June 30, 1975; and A. R. Frederickson, "Radiation-Induced Currents and Conductivity in Dielectric," IEEE Trans. Nucl. Sci. NS-24, December 1977.

2.3 FREE-FIELD ENVIRONMENTS

Free-field environment calculations were carried out to determine fields expected in the pipe and surrounding grout if no experiments were emplaced. The calculations assumed an axisymmetric geometry, with a conducting outer boundary representing mesh, pipes, and conduit at the outer wall of the grout-filled drift. Both one- and two-dimensional calculations of the environment were carried out. The one-dimensional model employed the localization assumption that the EMP fields, expressed as a function of radius r , axial displacement z , and "burst-retarded time" τ ($\tau = t - z/c$), vary rapidly with r and slowly with z at a fixed value of τ . This simplification allows one to carry out calculations of fields as a function of r and τ independently for each set of z values. Physically, the environments are localized by sufficiently high conductivity of air and grout (Refs. 8-10).

The two-dimensional calculations were made without the localization assumption noted above, and provided fields as a function of r , z , and τ (Ref. 11).

Geometry and other features assumed for the one- and two-dimensional environment calculations are shown in Figure 3. The expected air, pipe wall, and grout are terminated at an outer radius of about 2.5 m by a conducting cylinder representing deeply buried pipes, conduits, and wire mesh; the magnetic field at this extreme radius measures the return currents driven on such conductors in the absence of more direct connections (pipe-to-cable tray conduits). A radiation-enhancement factor for the grout conductivity was assumed, as indicated; the value of k chosen was $k = 2.2 \times 10^{-14}$ (mho/m)/(rad/sec). A single central conductor (assumed bare) was used for the calculations to be discussed here; additional cables are expected to be located at the pipe-air interface, and their effect should be to further decrease the spatial extension and level of the Compton current's return by providing more local return paths (an advantage) at the expense of some concentration of E- and H-fields in the vicinity of other instrumentation (a disadvantage).

Analytical representations of r -, z -, and time-dependent radiation environments, as calculated by W. H. Scott at SAI (Refs. 6,7) were used as the basic driving sources for the EM calculations. The representations were based upon range (down the pipe) dependent fits of early (prompt gamma flash) and late (fast neutron arrival) peak gamma-ray dose rates, variation with range of rise and decay times of the early and late components, and radial decay of the dose rate in the grout. Since directional characteristics of the gamma-ray driving radiation were not obtained as part of the original transport calculations, "reasonable" assumptions of such characteristics were made; the gamma-ray-associated Compton currents are axial in the pipe center and radial deep in the surrounding grout, with smooth variation between.

Peak dose rates as calculated by Scott were represented in their range variation by a z^{-a} dropoff, where a is ~ 2.8 . The departure from $a = 2$ (expected at close range to a point source) arises from the distributed nature of the source at short ranges and some distortion due to time-bin width at longer ranges.

Some general features of the drivers for the 3-foot pipe environments are summarized as a function of displacement down the 3-foot pipe in Table 4. The peak dose rates shown there reflect the $z^{-2.8}$ dropoff noted earlier; the peak Compton currents tabulated next are simply proportional to $\dot{\gamma}$. The

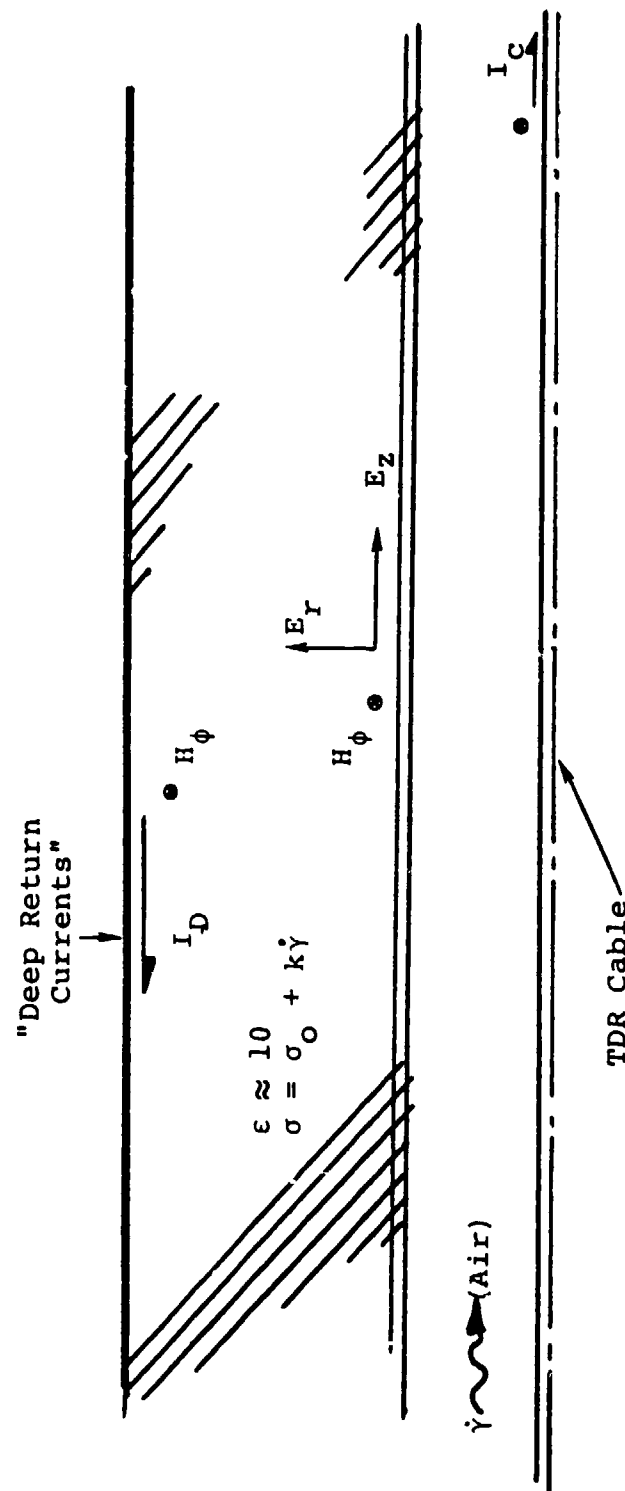


Figure 3. Pipe environment geometry for 1-D and 2-D calculations

Table 4. 3-Foot Pipe Environments (General)

	3 m	10 m	30 m	100 m
$\dot{\gamma}_{pk}$ (rad/sec)	1.5×10^{13}	5×10^{11}	3×10^{10}	8×10^8
$j_c(pk)$ (amp/m ²)	3×10^5	1×10^4	6×10^2	1.6×10^1
$\sigma_{air}(pk)$ (mho/m)	~ 5	~ 1	~ 0.1	3×10^{-3}
Environment	1-D	1-D	1-D 2-D	1-D 2-D

air conductivity near the time of peak $\dot{\gamma}$ depends upon the rise time of $\dot{\gamma}$ and the electric fields at peak time; the values shown are consistent with longer rise times of $\dot{\gamma}$ and lower electric fields at the more extended ranges. One important observation to be made is that the air and grout conductivity is sufficiently high that the environments are reasonably local (and 1-D) everywhere, except perhaps at the 100-m range point: the skin depth δ ($\delta = \sqrt{2/\mu\sigma\omega}$) is about 0.4 m for $\sigma = 0.1$ and $\omega = 10^8$; it only increases to 4 m for $\sigma = 0.01$ and $\omega = 10^7$.

Field and current levels are summarized in Table 5. Field values at peak $\dot{\gamma}$ time are tabulated at the wall (air/pipe wall interface) and at about 0.5 m into the grout ($r = 1$ m).

Return currents at the outer conducting boundary are shown at the bottom of Table 5 for times near the peak gamma-ray dose-rate intensity and at comparatively late times. Agreement between 1-D and 2-D predictions of the field intensities was found to be generally quite good. Peak early-time cable current on the central TDR cable was predicted to be somewhat larger with the 2-D calculation than with the 1-D calculation, indicating some non-local contribution to cable current at the 100-m range point. The indicated prediction of 60 amp is the high (2-D) value. Note that the Compton current density in the tunnel at 100 m is about 16 amp/m² at peak; the TDR cable current is thus perhaps somewhat more than one might expect if the conductivity in the pipe completely isolated one z (range) point from another.

Table 5. Summary of Typical Field/Current Levels

z =	3 m	10 m	30 m	100 m
<u>At Wall</u>				
E_r (V/m)	6.0×10^5	2.0×10^5	1.1×10^4	7.2×10^1
E_z (V/m)	2.0×10^5	4.0×10^4	2.3×10^3	4.2×10^1
H_ϕ (amp/m)	3.0×10^3	5.0×10^2	4.5×10^1	8.4×10^0
<u>At $r \approx 1$ m</u>				
E_r (V/m)	1.0×10^4	5.6×10^3	5.6×10^2	2.5×10^1
E_z (V/m)	1.4×10^5	2.0×10^4	8.8×10^2	1.4×10^1
H_ϕ (amp/m)	2.0×10^3	4.0×10^2	2.6×10^1	5.6×10^0
<u>Return Current (at $r \approx 2$ m) (amp)</u>				
($\sim 10^{-8}$)	5000	200	10	<1
($\sim 10^{-6}$)	500	10	2-5	<1
TDR cable currents at 100 m \approx 60 amp				

Variation of the environments with peak dose rate shows a rather slower variation overall than direct proportionality. This arises from a number of factors, including (probably most importantly) saturation of the fields (with high conductivity at the closer ranges), changes in the time-shape of the radiation pulse with range, and balance of return currents between TDR cable, air, and grout as a function of range (or air conductivity).

Typical results of the 1-D calculations for the 3-foot pipe are shown in Figures 4 and 5, which show radial profiles of the fields at fixed values of (retarded) time after the peak radiation dose-rate intensity. Time histories of the fields at points near the air-grout interface and at points somewhat deeper in the grout are shown in Figures 6 and 7.

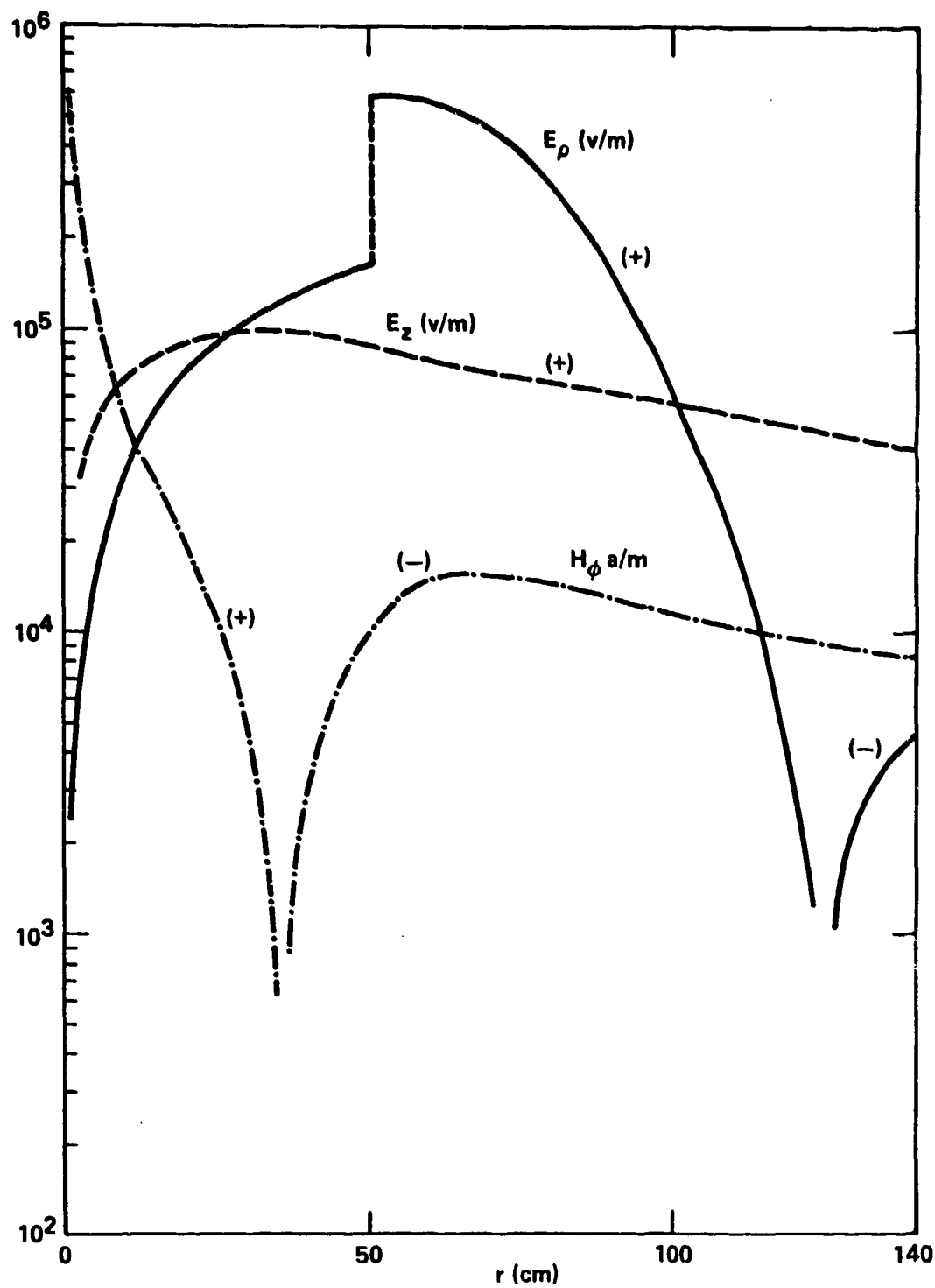


Figure 4. Fields as a function of radius at $t = 1 \times 10^{-7}$ sec and $z = 3$ m

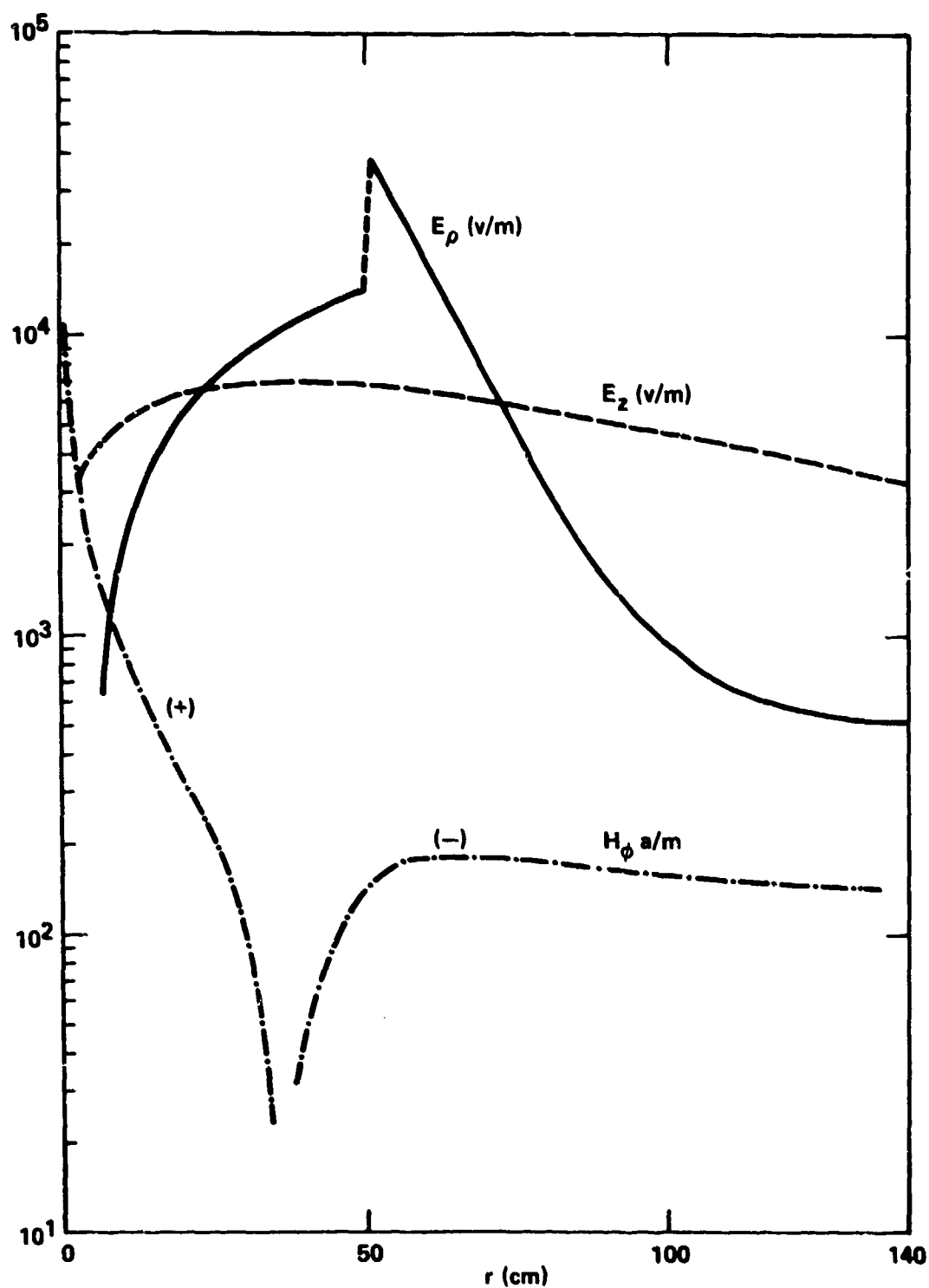


Figure 5. Fields as a function of radius at $t = 1 \times 10^{-7}$ sec and $z = 10$ m

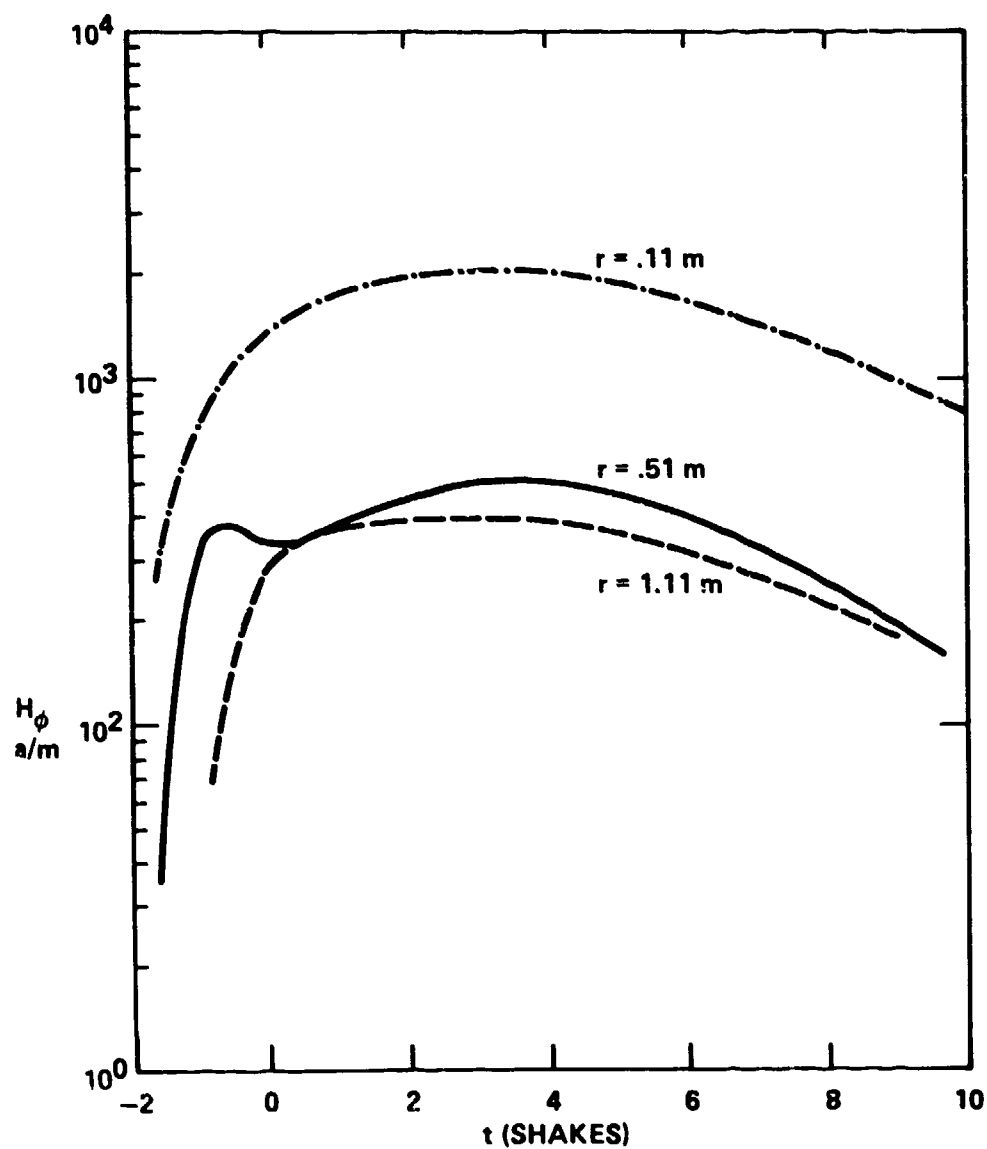


Figure 6. Time histories of the magnetic field at $z = 10$ m and the indicated radial depths

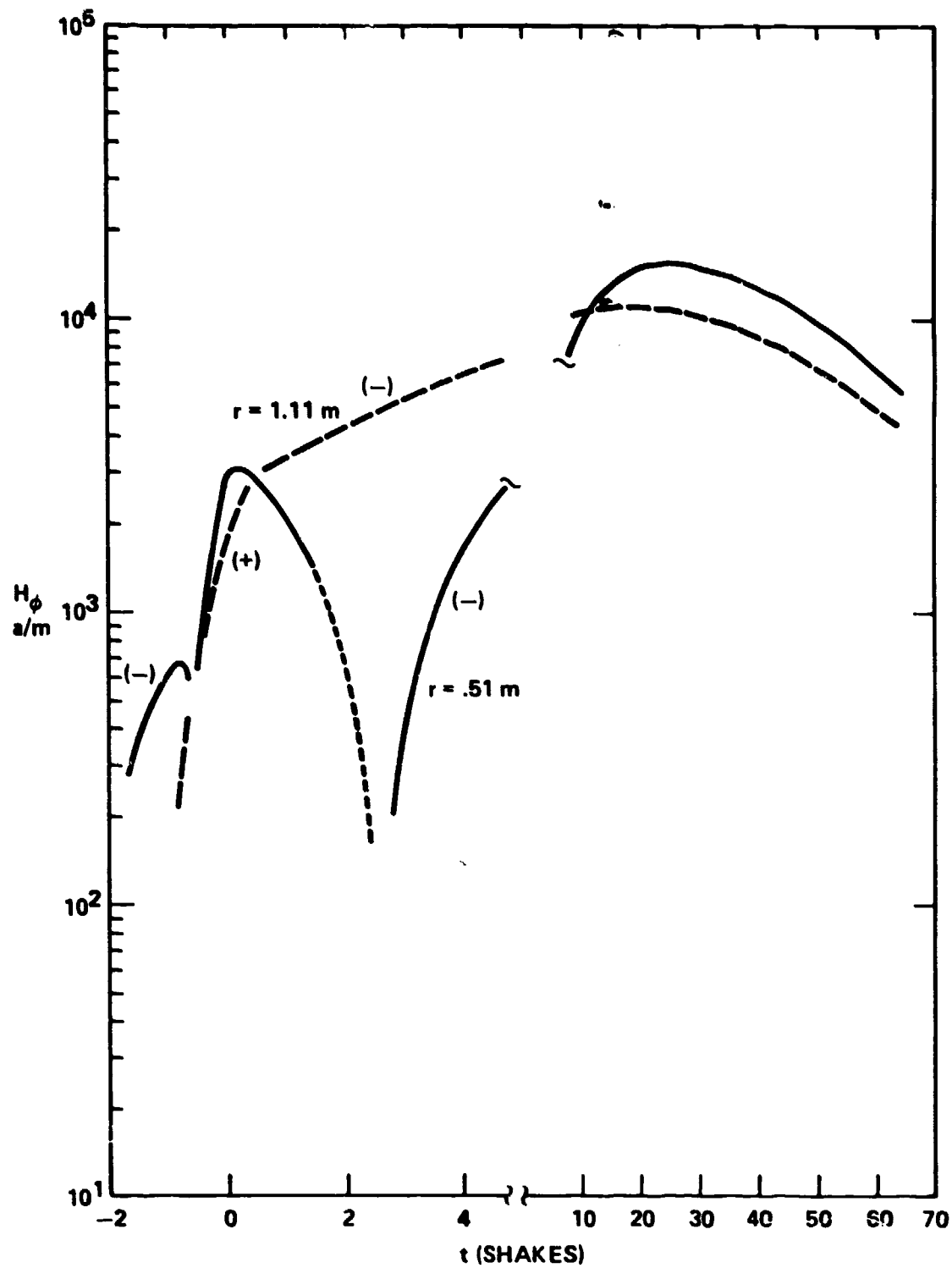


Figure 7. Time histories of the magnetic field at $z = 3 \text{ m}$ and the indicated radial depths

3. EXTERNAL SHIELD CURRENTS

In this section, we outline an estimate (or several related estimates) of the primary (exterior) shield currents and their effects. The first concern will be shield current generation at the gauge location; attenuation and coupling beyond the gauges will then be discussed. "Downstream" cross-coupling problems and hardening are considered elsewhere (Ref. 12).

3.1 INITIAL (NEAR-GAUGE) SHIELD CURRENTS

Referring to Figure 2, our basic model for estimating the magnitude of exterior shield currents will be based on a local coupling model for early times and on the free-field environment at later times. The basic idea is that gamma radiation local to the gauge will be most important in determining the initial shield current levels, while later currents will be due to drivers in a larger volume of space that includes the pipe and return paths (such as the mesh or cable tray) deep in the grout. An appropriate time scale for transition between these regimes might be one corresponding to a skin depth of about 1 m (in grout of conductivity of about 0.02 mho/m), or very roughly 10^{-8} sec.

Coupling in the local model was examined via the 2-D environment calculation. The point of the calculation was to determine local fields driven by gamma radiation in the grout outside the gauge. Such fields then give current levels on the instrumentation package exterior shield. The geometries considered are shown in Figure 8.

Typical dimensions for the external coupling problem were chosen to represent a shield embedded in grout with the possibility of return via metallic conductors at some distance from the package. The shield lengths are typically 2 m, running from near the pipe wall to the shielded cable tray, and radii of 1 and 4 cm were assumed as representative transverse dimensions.

The first set of external results shown (Table 6) summarize calculations for a large-gauge outer shield such as the SRI close-in pressure gauges. Two situations were considered: first, a gauge with front face close to the surface

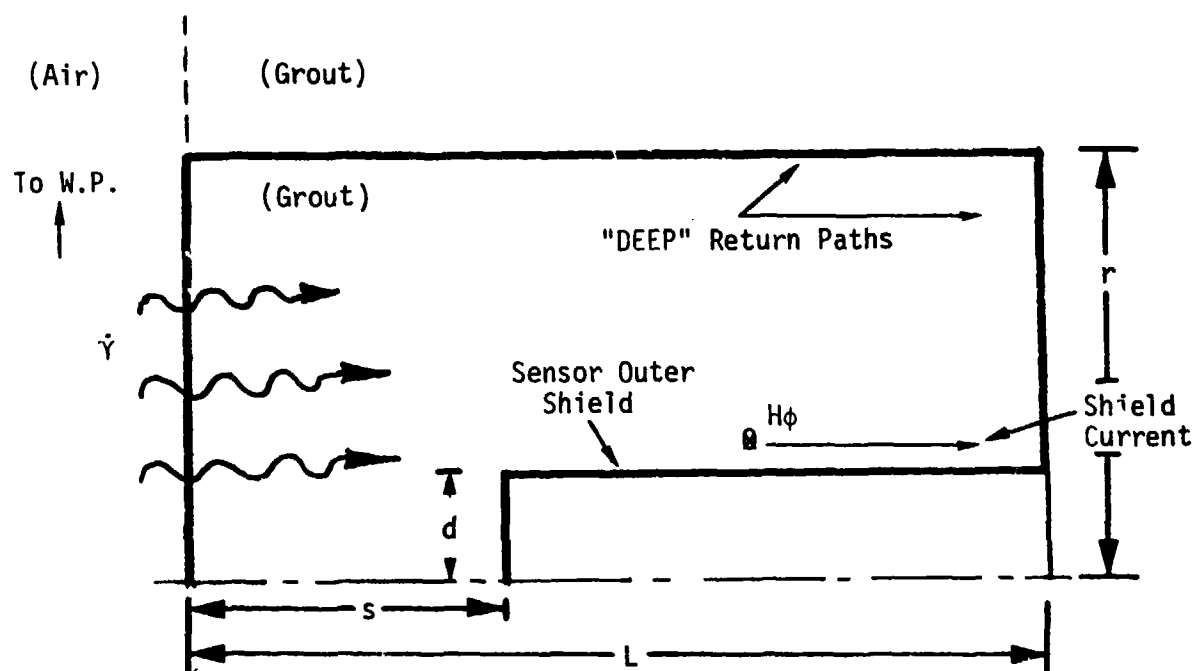


Figure 8. Sketch of external coupling geometry

Table 6. Summary of External Coupling Levels

Large Gauge (SRI)

Overall length, L	2 m
Outer radius, r	1 m
Inner radius, d	4 cm
At 1 meter ($\dot{\gamma} \approx 5 \times 10^{14}$)	
I(0), current at front end of probe (probe at 1 cm depth)	2×10^5 amp
I(2), current at rear end of probe (probe at 1 cm depth)	250 amp
(probe at 50 cm depth)	2000 amp

Small Gauge

Overall length, L	2 m
Outer radius, r	1 m
Inner radius, d	1 cm
At 10 meters ($\dot{\gamma} \approx 5 \times 10^{11}$)	
I(0) ($\Delta T \approx 10^{-8}$)	~ 200 amp
I(2) ($\Delta T \approx 5 \times 10^{-8}$)	~ 300 amp

of irradiation (1 cm) and approximately 2 m long, and second, a gauge buried more deeply in the grout (front surface 50 cm from the irradiated grout surface) and correspondingly shorter (1.5 m). The diameter of the gauge body was 8 cm in both cases. Exterior current at the root of the gauge body (next to the cable trough and far from the radiation) were 250 amp for the first case, close exposure, and 2000 amp for the second, lesser exposure. The reasons for the apparent discrepancy is simply that the return current path for local driven currents is perforce through the root of the gauge for the second case. Currents for "far" exposure would, of course, eventually decrease with withdrawal of the gauge, due to the exponential attenuation of the gamma radiation reaching the front end of the gauge. Exterior currents for a smaller long gauge (~ 1 cm radius) buried ~ 1 cm beneath the irradiated surface are shown in the second example in Table 6. Current values are quoted near the front and near the back of the gauge.

3.2 CURRENT ATTENUATION BEYOND GAUGES

Once established on conduits or cables, shield currents may flow for some distance, coupling interference signals into interior circuits via the transfer impedances of shields and connectors or other imperfect joints. Grout surrounding the shield can attenuate the current, either through ohmic contact with a bare conductor or through capacitive coupling, if there is an insulating dielectric covering on the shield. While shield current generated near the gauges is expected to remain primarily on the cable tray exterior (see Figure 2), some excitation of cable shield currents inside the tray (due to various leakage mechanisms such as are discussed in Section 3.3) is inevitable. Interior shield currents are attenuated with distance down the inside of the cable tray, and an estimate of such attenuation rates, based on a simple circuit representation of a lossy TEM transmission, was constructed.

We will consider two cases in the model: If ω_0 is the frequency at which the skin depth δ in grout is comparable with tray dimensions D_g , then (as indicated in Figure 9) the transmission-line equivalent involves inner and outer conductors at the cable shield and tray wall for $\omega < \omega_0$; if $\omega > \omega_0$, the "outer conductor" is moved inward from the tray wall to a distance of about one skin

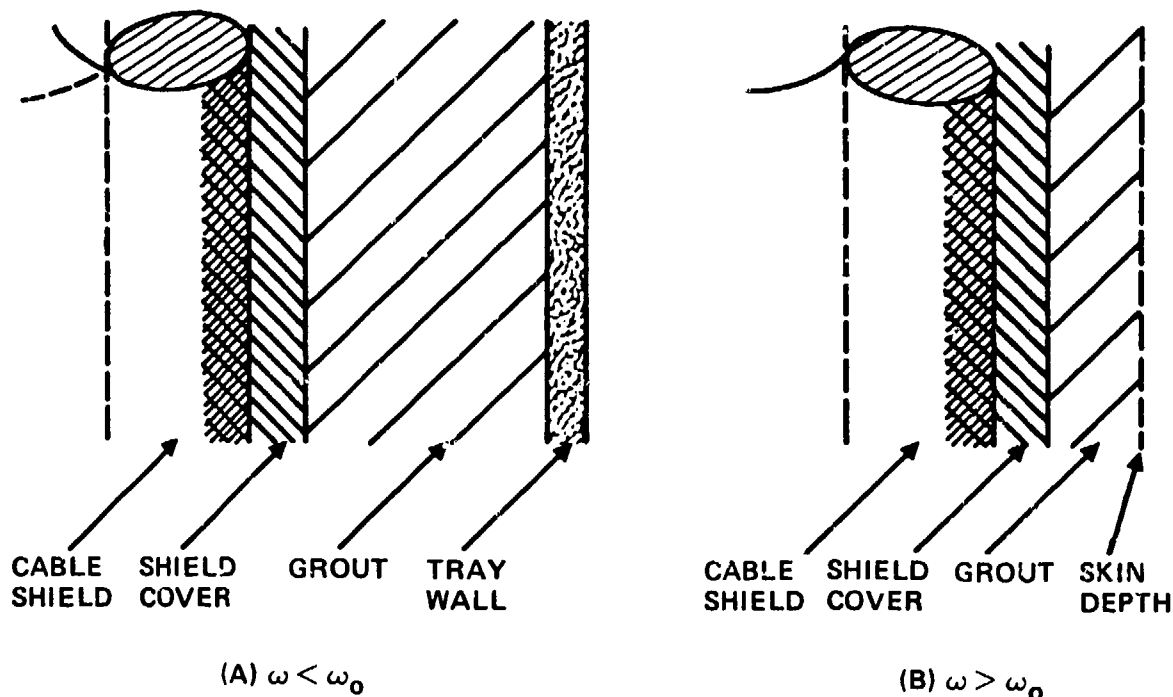


Figure 9. Sketch of elements of the transmission-line model for shield-current attenuation

depth from the cable shield. This model is applicable up to and perhaps somewhat beyond the cutoff frequency, but the frequencies of interest in the present problem are, perhaps fortunately, mostly in the lower range.*

For all values of ω , our model will be that of a unit length of the transmission line shown in Figure 10. The propagation constant for the transmission line, $\alpha(\omega) + j\beta(\omega)$, gives the signal amplitude $A(z)$ propagating down the cable sheath:

$$A(z) \approx \exp\{[\alpha(\omega) + j\beta(\omega)]z\} .$$

In terms of the series and parallel impedances Z_1 and Z_2 (indicated in Figure 10), the propagation constant is just

*The author is indebted to Dr. C. T. C. Mo for tactful clarification on this point, as well as helpful suggestions in model formulation.

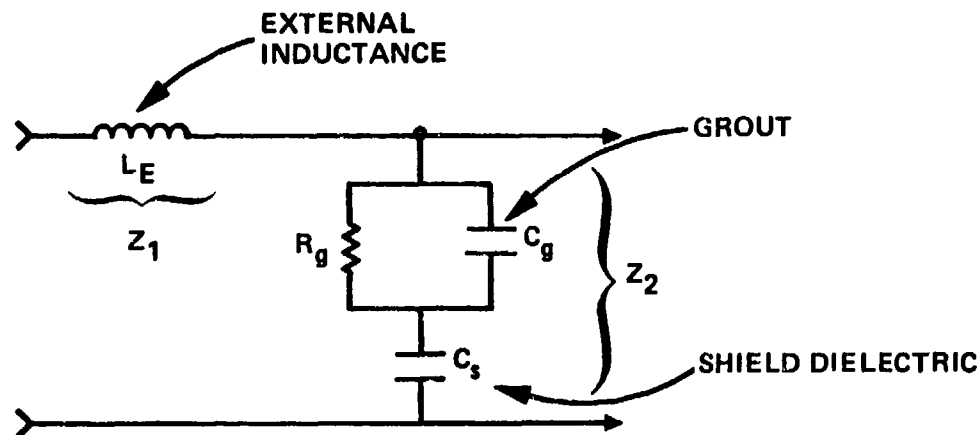


Figure 10. Circuit elements in the TEM transmission line described in the text and sketched in Figure 12

$$\alpha + j\beta + \sqrt{\frac{Z_1}{Z_2}}$$

and algebra for the circuit in Figure 10 yields

$$Z_1 = j\omega L_E,$$

$$Z_2 = \frac{1}{j\omega C_s} + \left[\frac{R_g}{R_g} + j\omega C_g \right]^{-1},$$

and

$$\alpha + j\beta = \sqrt{(j\omega L_E)(j\omega C_s)} \left[\frac{1 + j\omega C_g R_g}{1 + j\omega(C_g R_g + C_s R_g)} \right]^{1/2}.$$

The circuit elements C_g , R_g , and L_E are, of course, simple functions of the transmission-line dimensions and parameters, and must be evaluated in the two limits $\delta < D_g$ and $\delta > D_g$. Characteristic attenuation distances (measured by α^{-1}) are plotted as a function of frequency in Figure 11 for a few parameter values in the regime of interest. We should note that the "true" grout parameters are functions of frequency; some typical values for grout used in other shots: at 1 MHz, $\sigma \approx 2 \times 10^{-3}$, and $\epsilon = 35$, while $\sigma \approx 5 \times 10^{-3}$ and $\epsilon \approx 18$ at 10 MHz. The cutoff frequency, f_0 , is estimated by:

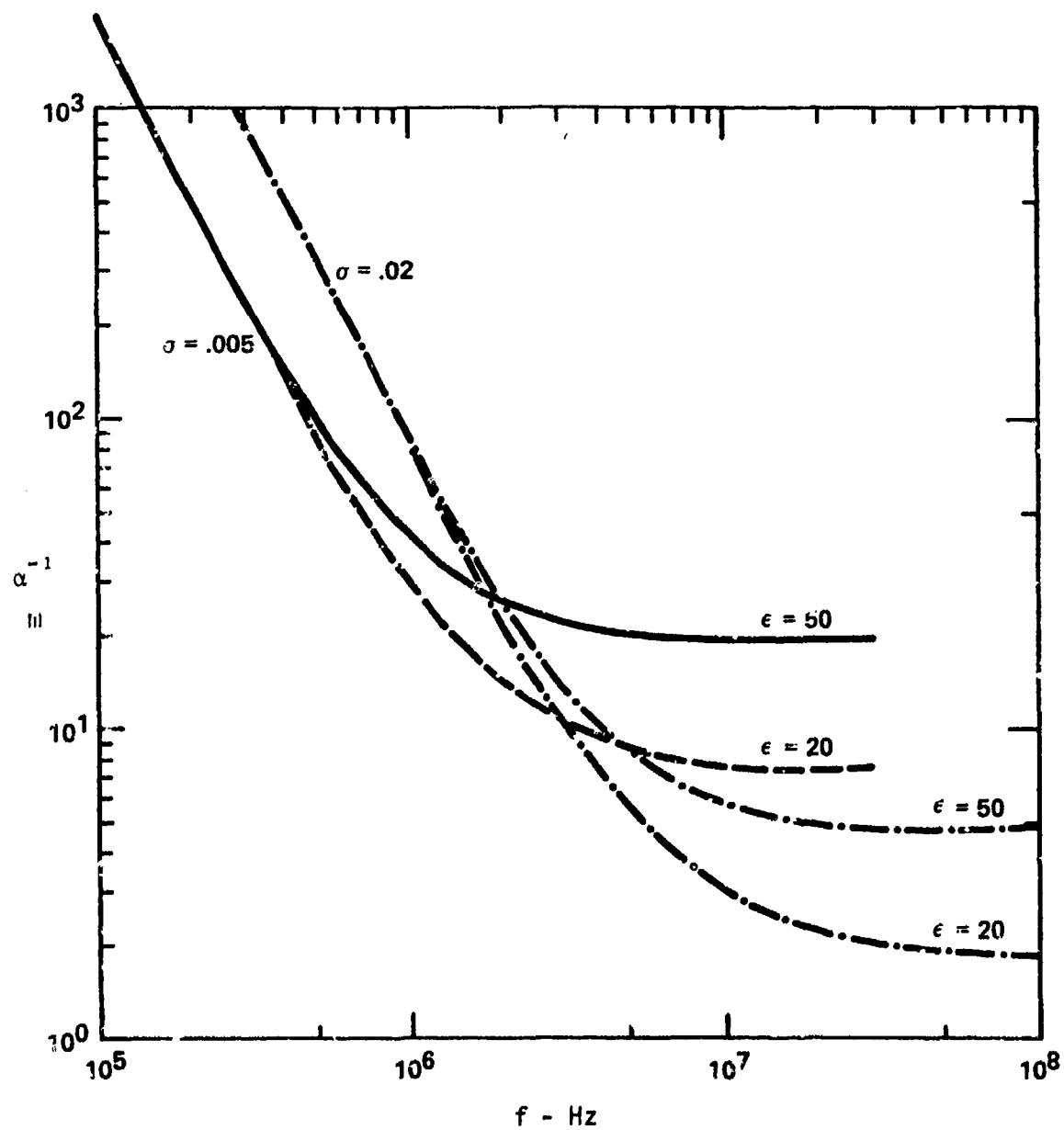


Figure 11. Attenuation lengths vs. frequency for shield currents on grouted cable

$$f_0 = \frac{\omega_0}{2\pi} = \frac{1}{\pi\mu_0\sigma\delta^2}$$

and is about 317 MHz for $\sigma = 0.02$ mho/m and $\delta = 0.2$ m.

3.3 EXTERNAL/INTERNAL COUPLING ESTIMATES

Coupling between adjacent levels of transmission-line shielding (e.g., primary shield-secondary shield, or secondary shield-signal wire) can be analyzed in considerable detail, if necessary. Convenient basic concepts in the development of a transmission-line analysis are the transfer impedance Z_T and transfer admittance Y_T characteristics of a shield. Referring the reader to various excellent general discussions (Ref. 4) for details and applications, we briefly summarize the concept here by reference to Figure 12, which shows the effects of external shield currents I_e and voltages V_e at some point in an external circuit that includes the shield of a transmission line. Voltages and currents in the internal transmission line are built up via transmission-line equations in which $Z_T I_e$ and $Y_T V_e$ figure as voltage and current source densities, respectively. Electrically short, open, or long transmission lines provide various simplifications, and the complication of nested shields can be handled in stages.

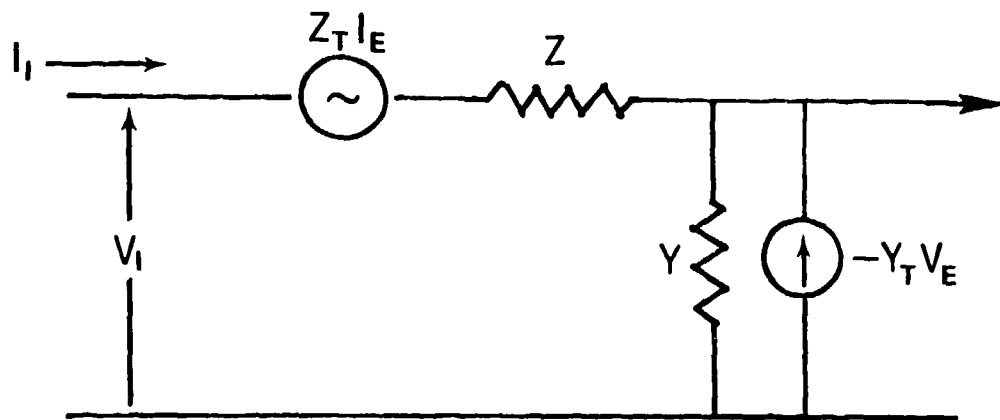


Figure 12. Transmission-line representation of external/internal coupling phenomena. I_1 and V_1 are internal current and voltage on the transmission line with the (unit-length) parameters Z and Y . Z_T and Y_T are transfer parameters for external voltages and currents V_e and I_e .

At dc, the transfer impedance per unit length of a shield is essentially R_0 , its resistance per unit length; at higher frequencies, Z_T for a solid shield becomes much smaller than R_0 (through skin-depth attenuation), while braided shields (after some improvement at intermediate frequencies) become leakier with increasing frequency and Z_T becomes predominantly inductive. Typical values of R_0 and mutual inductances M_{12} are 5 to 10 mΩ/m and 0.2 to 0.5 nH/m, respectively.

Joints and connectors can usually be well characterized by a transfer impedance only; measured connector characterizations given in Reference 4 express Z_T as

$$Z_T = R_0 + j\omega M_{12} ,$$

where R_0 is typically in the range 0.005 to 0.05 ohm and M_{12} is typically 2 to 5×10^{-11} H. While values for very poor connections or connectors may range upward to kilohms of resistance and nanohenries of inductance, we may perhaps choose "optimistic" bad values of R_0 in the 0.1 to 1 ohm range.

The leakage estimates outlined here can be applied at many of the interfaces identifiable in Figure 2. We will postpone such further details to Section 5.

4. INTERNALLY GENERATED SIGNALS

4.1 COUPLING MODELS

Internally generated signals can be estimated using the same methods that were discussed earlier in connection with external-shield currents. The general geometry that was considered is sketched in Figure 13; except for characteristic dimensions and the terminating load resistor, it is clear that the internal and external coupling geometries are the same. The outer boundary of the present problem is the case shield for the gauge, while the internal conductor represents the output path (usually for common-mode signals) to the signal-conditioning electronics.

4.2 SUMMARY OF INTERNAL COUPLING RESULTS

Coupling calculations for a few typical geometries and irradiation levels were carried out. Internal coupling geometries were chosen with outer shield (outer boundary) dimensions a in the range noted in Section 3 and quite small internal conductors (0.02 cm radius, or about 20 mil diameter); representative impedances to ground were used.

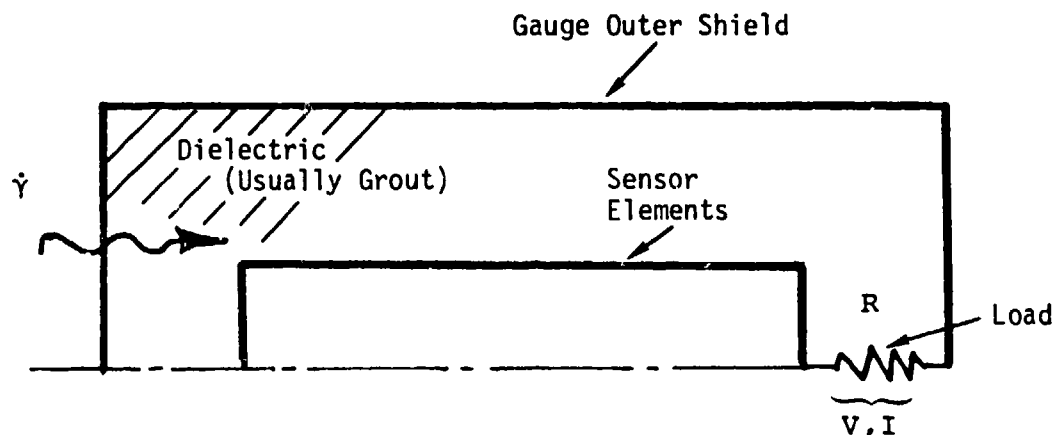


Figure 13. Sketch of internal coupling geometry

Internal signals obtained are shown at the irradiation level in Table 7. Characteristic voltages across the load resistances are shown (together with typical characteristic times) first for a large gauge such as the S³ ablation gauge. A small wire embedded in grout represents the common-mode pickup of the sensing element. The second, small-gauge results are shown for a similar problem, with the grout replaced by a dielectric medium of much lower ambient conductivity. As in the case of the external-coupling calculations, results do not scale simply with irradiation level, because of the enhanced conductivity of the ambient medium. At low dose rates (far ranges), linear scaling with dose rate is reasonable.

Table 7. Summary of Internal Coupling Levels

Large Gauge (S³ Ablation)

L = 2 m, r = 8 cm, d = 0.04 cm
 R = 50 ohm, grout-filled
 At 10 m ($\dot{\gamma} \approx 5 \times 10^{11}$)
 $V_Z = 120$ volts, $\Delta T = 2 \times 10^{-8}$ sec

Small Gauge (SRI Ablation)

L = 2 m; r = 1 cm; d = 0.04 cm
 R = 0.1 ohm, SiO₂-filled
 At 10 m ($\dot{\gamma} \approx 5 \times 10^{11}$)
 $V_Z = <2$ volts

5. SUMMARY AND CONCLUSIONS

In the foregoing sections, important aspects of the radiation-associated electromagnetic interference problem for typical Hybla Gold sensors have been discussed. We will here attempt to collect and summarize the various considerations that were detailed earlier. Quantitative characterization of the various components of the interference are summarized in Table 8 as a function of range; the significance of various entries in the table will be discussed briefly below.

Direct-drive signals arise from gamma radiation directly incident on the sensor element, and are unaffected by ordinary EM shielding. The magnitude of the current source driving such signals is reduced by radiation shielding, by suitably small and symmetric geometric design and orientation of the sensor, and by materials choices that minimize the imbalance between ON- and OFF-driven Compton currents. Based on sensor electrode transverse dimensions, and 10 or 20 cm of significant irradiation along the sensor length, cable response figures, as well as a real current density coefficient, suggest that a reasonable estimate for sensor response should be less than about 10^{-12} amp per rad/sec of exposure. Results for this estimate (pessimistic in terms of materials imbalance and shunting conductivity and because irradiation is more lengthwise than sidewise for most sensors) are shown in Table 8, together with associated dose-rate levels at the air/grout interface for the 3-foot pipe, as a function of range and time.

Internal signals are also related to local radiation dose rates, but are driven through the intermediary of longitudinal fields in the immediate vicinity of the sensor elements. Results for signals levels discussed in Section 4.2 are shown in Table 8 below the direct-drive interference components.

Primary shield currents should couple into internal circuitry mostly through leakage at joints and through the transfer impedance of long cable shield segments. Based on an 0.1-ohm transfer impedance at the tray-primary shield joint (see Figure 2), exterior shield currents in the tray should be down by about 40 dB from those on the gauge primary shield. As discussed in Section 3.2, high-frequency components ($>10^7$ Hz) should bleed off within

about 10 m, but frequencies below about 1 MHz are probably not significantly attenuated. One should also expect cross-coupling between cable shields (not analyzed) to redistribute currents brought into the tray on a single cable to other cable shields as well. Cable tray shield currents expected on this basis are shown in Table 8 together with primary shield currents, at early and at late times. Early-time shield currents are based on the local coupling model discussed in Section 3.1, while late-time currents are based on the larger return paths involved in the free-field environments discussed in Section 2. Internal voltages found from the cable shield transfer impedances noted in Section 3.3 are tabulated last. It is to be noted that the internal voltage is typically a common-mode voltage; the effective value of the interference will be less, depending on the balance of the circuitry involved.

The interference levels shown in Table 8 indicate that moderately careful design and construction of the gauges and associated signal-processing equipment should be sufficient to ensure their survival to the beginning of measurement time. The expected EM interference levels from "front end" sources at times beyond 100 μ sec are extremely low; interference due to shock- and plasma-related phenomena and ringing in the cable plant (observed in other shots) will probably predominate during measurement time.

Table 8. Interference Signal Summary

	Early	Late	Units
<u>Close-In Locations</u> (R \approx 1 m)			
$\dot{\gamma}$	5×10^{14}	5×10^{10}	(rad/sec)
Sensor direct	~ 500	5×10^{-2}	(amp)
Sensor internal	(Below direct levels)		
Sensor shield	~ 2000	~ 200	(amp)
Shield in cable tray	~ 20	< 2	(amp)
Cable core	< 2	< 2	(volt, common-mode)
<u>R \approx 10 m</u>			
$\dot{\gamma}$	$\sim 5 \times 10^{11}$	$\sim 1 \times 10^9$	(rad/sec)
Sensor direct	< 0.5	$< 10^{-3}$	(amp)
Sensor internal	~ 100 (high impedance)		
	< 2 (low impedance)		
Sensor shield	300	< 10	(amp)
Shield in cable tray	3	< 0.1	(amp)
Cable core	< 0.3	< 0.1	(volt, common-mode)

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APPENDIX A

HYBLA GOLD CABLE GROUNDING PLAN
UNIFIED APPROACH
REVISED APRIL 21, 1977

HYBLA GOLD CABLE GROUNDING PLAN

- UNIFIED APPROACH -

Revision 21 April 77

INTRODUCTION

Since the inception of the underground test (UGT) program there have been controversies as to what the proper grounding and shielding techniques should be to obtain valid data. Many experimenters have adopted systems based on non-UGT recording environments as well as trial and error methods that have worked on previous tests. As a result, there has never been a unified approach to grounding. On any test we find combinations of single point grounds, multipoint grounds and floating recording channels.

This plan describes the dominant UGT noise sources and proposed cable handling techniques to minimize their effect on data recording. The unified approach requires that all experimenters conform to the plan in order to successfully obtain valid data on the Hybla Gold event.

NOISE SOURCES

The dominant noise source that a UGT recording system is subjected to is direct irradiation of sensors and signal cables that cause compton replacement currents to flow on signal cable shields and center conductors. Also associated with ionizing radiation are electric and magnetic fields that couple to susceptible recording system sensors and signal cables.

Intense photo currents and electromagnetic signals are generated by the prompt ionizing radiation that are time distributed along exposed lengths of experiment pipes and cables. The signal strength decreases as a function of $1/r^2$ with respect to the radiation source. Thus we find a variable current density throughout the experiment bed that results in a wide range of signal amplitude and frequency components. Once these currents are generated they may

result in localized recombination; however, the tendency will be for them to propagate on various transmission lines such as pipes, signal cables, power cables, railroad tracks, etc. As a result, signals may persist for a long time period if allowed to propagate on improperly terminated transmission lines.

In addition to the prompt gamma induced signals the device emitted neutrons generate similar signals, having a time distribution that is a function of energy and distance from the source. Also captured neutrons result in long term n- γ reactions.

There are other noise sources such as ground currents and disruption of the local earth magnetic field. In the mesa trailer park, the signal cables are exposed to atmospheric disturbances and coupling from 60 Hz power systems. These effects are small compared to the previously described noise.

NOISE INJECTION

There are a number of ways that noise generated, as described in the previous section, can be coupled into the recording system. Direct radiation exposure of sensors and connecting cables results in internal compton replacement currents and conduction currents. Careful design and materials selection are required to reduce this effect. Of greater concern are signals that are allowed to propagate throughout the cable plant and couple into signal cables. There are several mechanisms that allow signals on cable shields to penetrate into the cable. Cable connectors and splices are potential ports of entry for RF noise. Also, braided cable shields are leaky at frequencies above 100 MHz with a coupling coefficient that is a function of the braid spacing. At lower frequencies (i.e., < 100 kHz) the cable shield is shallow as compared to a skin depth of several mm, thus allowing

signal coupling that is a function of the shield transfer impedance.

GROUNDING, SHIELDING AND ISOLATION (Ref Print LVC-203, Sheet 1)

The first line of defense to minimize propagation of signals on transmission line shields is to earth ground them at selected intervals. Data collected on previous events * show that impulse currents that propagate into the central cable plant excite other cables in close proximity. After the plant is excited the energy on a cable shield dissipates as a function of its terminating impedance (i.e., the lower the impedance, the faster it damps out). Thus, grounding serves two purposes: (1) It minimizes impulse current propagation into the central plant, and (2) those signals that are coupled are damped out rapidly.

It is anticipated at this point that arguments will be raised that multiple grounds enhance magnetic coupling, therefore introducing noise into the system. That is true; however, the shield currents are a greater problem. As a result, we must treat the current first and employ techniques to minimize the ground loop effects second.

Grounding of cable shields and sensor enclosures in areas that are exposed to ionizing radiation is particularly important. Again, grounding at this point serves several purposes: (1) Compton replacement currents are returned to the local generation source rather than propagating throughout the cable plant and finally returning to the source for equalization to be achieved. (2) Floating systems may be elevated in potential relative to the surrounding media and other experiments to the point where breakdown (arcing) may occur. This then can result in RF noise that may be coupled to other experiments. Distributed grounds are recommended along the experiment pipes at points where various experiment cables juncture. Thus, signals from different source

* Mighty Epic Cable Noise Study, SAI Technical Report LV-103

points are noded to the local ground reference. The present plan is to route all signal cables within a cable pipe to which the cable shields will be attached.

A second line of defense is to run the signal and excitation cables within a second shield. The outer shield will serve to carry the bulk of the external noise. For Hybla Gold, it is proposed that double shielded cable be run from the gage to the cable pipe. Both the inner and the outer shield are to be connected at the gage shield interface and at the cable pipe interface (see print LVC 203, sheet 5). The cable pipe will run parallel to the experiment pipes, terminating at the end of the pipe drift. At this location, the cable bundle should be wrapped with wire mesh (i.e., chicken wire) that is attached to the cable pipe. The mesh should enclose the bundle and extend to the cable gas block to which it is also attached. It should also attach to the opposite side of the gas block bulkhead and extend to the junction box near the signal conditioning alcove (see print LVC 207, sheets 1 and 2). The shields will attach to the junction box bulkhead. This will be the common point for the cable shields from the auxilliary drift cable pipe, the T&F cable pipe, and the main drift cable pipe.

A point that must be recognized is that earth ground is a relative concept that applies to the localized media. Within the radiation environment the media, as well as experimental materials, are ionized resulting in a 'fluid ground' relative to other points throughout the cable plant. As a result, local grounds may be elevated relative to other points within the plant. Recognizing this fact, the distributed ground concept plays an important role. Multiple grounds along a distributed irradiated media tend to short out potential differences and minimize current flow between fluid grounds and the static grounds found in the non-radiation environment.

As previously pointed out, earth ground is a relative notion.

There is no such thing as a perfect ground, even under ideal conditions. Under 'ideal conditions' a good static ground may measure several ohms, however, multiple grounding reduces the ohmic value. The 'fluid ground' in the radiation environment tends to be a better local ground due to the radiation induced conductivity in the media.

Ferrite cores may be placed on all cables routed from the main cable bundle to the signal conditioning alcove. The cable shields are connected together in order to bypass shield currents while the ferrites provide RF isolation for the signal conditioning electronics which are floating with respect to ground. The signal conditioning alcove should be located in a relatively clean environment (i.e., no direct irradiation and minimal EMP effects). The signal conditioning electronics should also be mounted in RFI hardened enclosures and decoupled from instrument power.

Cable plant earth grounds should be placed at $1/10$ wavelength intervals relative to the 10 kHz to 100 kHz cable plant resonance that has been observed on previous events. This implies that intervals should be no greater than 1000 feet. Within the tunnel complex this is easily effected by placing ground nodes at cable gas blocks, overburden plugs, and splice racks. In addition, cables entering the uphole drill hole should be connected to the drill hole casing. This should force cable shield currents to the outside of the casing which appears as a long grounded cylinder. On the mesa, all cables should be grounded at the mesa splice rack where they exit the drill pipes. Also the cable shields should be connected to the floating trailer shell that acts as a farady cage. As a result, all trailers are connected to a common ground that is distributed throughout the tunnel complex.

Power to operate the trailers should be provided by isolated diesel or motor generators to eliminate ground loops between the instrumentation system and the commercial 60 Hz power system

which carries distributed safety grounds as well as neutral to ground connections at main distribution busses.

MESA NOISE AND CABLE HANDLING

Another noise source that has been mentioned is atmospheric noise that the mesa trailers and cable runs are exposed to. Also, 60 Hz irradiation by local power distribution systems can be a problem.

The atmospheric noise can be decoupled to the single point ground and by using quality shielded cables this should not cause problems providing that the cable run to ground length meets the $1/10$ wavelength criteria. Typical atmospheric noise including lightning strokes will have frequency components of less than 50 kHz.

The 60 Hz radiation may be more of a problem. This type of noise is primarily picked up by cable loops (magnetic induction). Therefore, each trailer should be floating and tied only to the one point ground. All signal cables should be routed close together in order to minimize loop areas. Also, power distribution cables should be routed perpendicular to signal cable runs to minimize coupling.

TUNNEL CABLE HANDLING

In the tunnel cable plant where intense radiation generated currents are expected, a number of techniques must be employed to ensure proper grounding and connector bypassing to minimize injection of noise at potential signal system ports of entry.

Drawings LVC 203, Sheets 2, 3, 4, and 5, depict methods of bonding cable shields to ground busses and methods of bypassing currents around cable connectors.

Also, cable runs should be routed close together in order to minimize loop areas subjected to magnetic pickup. These cables should be laid close to earth to effect a low impedance ground plane as well as minimize the earth ground loop area.

CABLE SELECTION

The following criteria is recommended for selection of cable type in the cable plant:

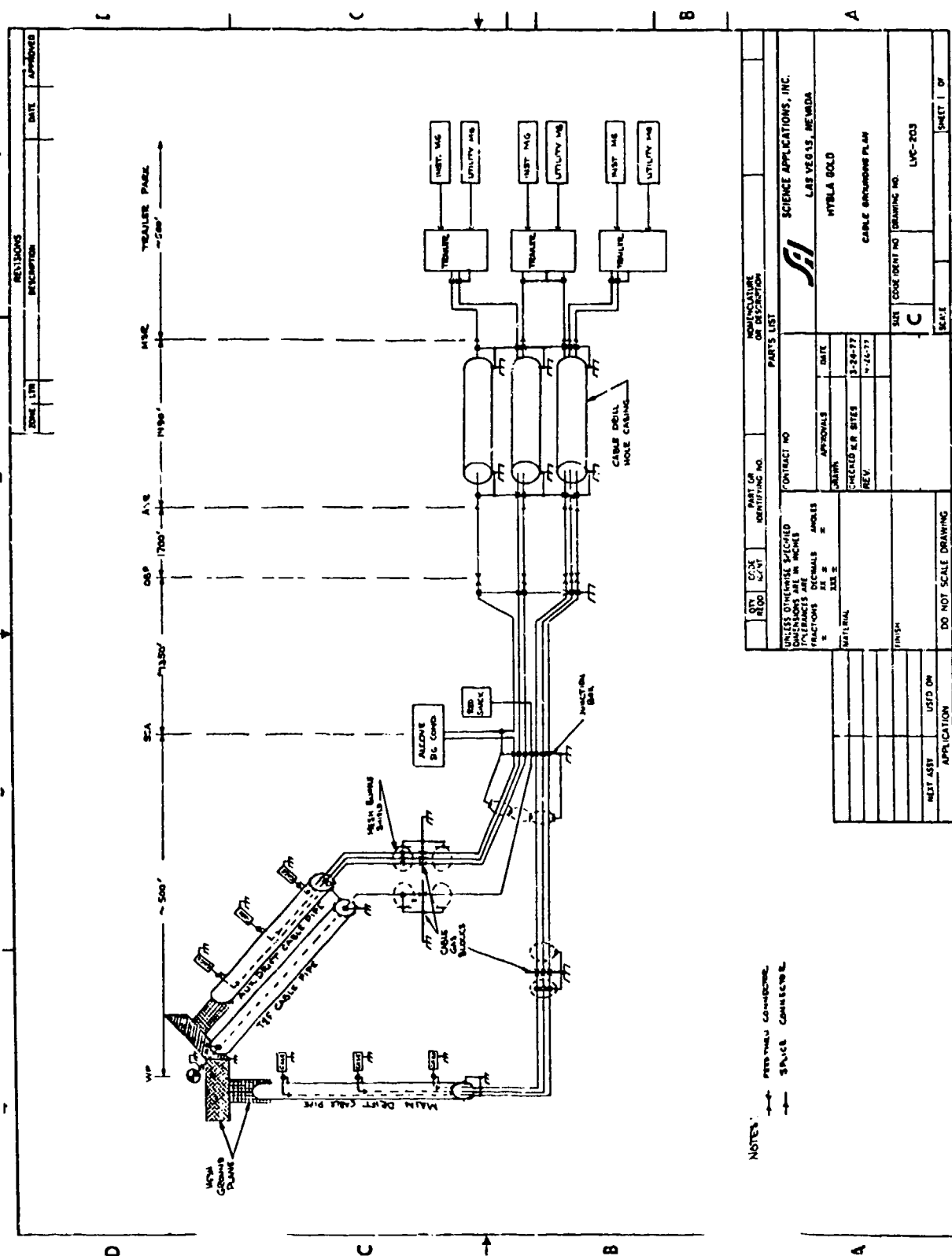
In the area of the experiment pipes coax cables such as solid shield RG-333/U, RG-331/U, or double thickness braided coax such as RG-22B/U and RG-214/U are recommended. TSP cable is not recommended due to its poor shield and current handling capabilities.

Balanced systems are recommended in this environment (RG-22B/U) with conversion to an unbalanced transmission system in a clean area such as the signal conditioning alcove.

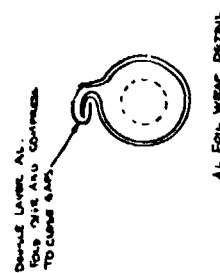
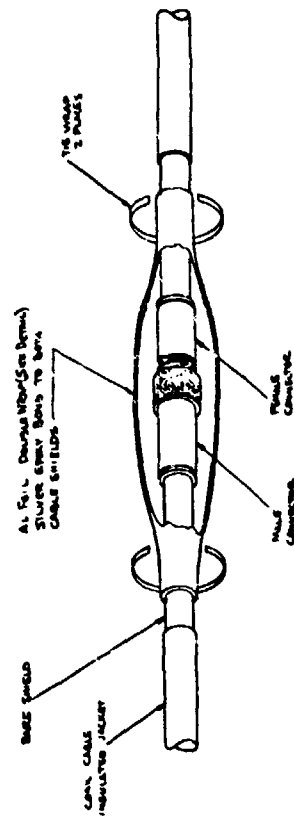
OTHER TRANSMISSION LINES

Much has been said about signal cables and methods to reduce noise. Equally important is proper treatment of other transmission lines such as water pipes, vent pipes, railroad tracks, power cables, etc. Many of these lines are routed within the radiation environment and therefore can carry heavy currents into the central cable plant to be reradiated onto the signal cables.

The general fix for this type of transmission line is to ground them everywhere possible and minimize their signal propagation ability. Power cables that cannot be grounded should be decoupled to ground by use of RFI filters. Care must be taken not to overlook these potential transmission lines.





[illegible][illegible]



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APPENDIX B

GROUNDING & SHIELDING PRESENTATION
NOVEMBER 1977

Grounding & Shielding

A. Background

On previous underground tests, significant noise has been present within the instrumentation system. A large part of this noise is attributed to the cable plant response to event generated radiation. The HYBLA GOLD grounding and shielding techniques were directed at reducing such noise through the following four methods: 1). provide a return path for radiation induced currents that were totally independent of the instrumentation system; 2). minimize noise currents reaching instrumentation cable shields; 3). provide methods to bleed noise signals to ground that did reach cable shields; and 4). minimize overall effect of remaining noise by spreading it over all channels. The evolution and final implementation of each are detailed below.

B. Provide Return Current Path

Steel cable trays in each drift provide the primary return paths for these currents. The zero room was originally envisioned as a Faraday cage of one inch mesh "chicken" wire joined to both cable trays, but since the back and side faces of the zero room were considered to be less significant to the objectives, the mesh was reduced to cover only the outside zero room walls facing the main and auxiliary drifts and joined to the respective cable trays.

C. Minimize Noise Reaching Signal Cable Shields

All gages were required to be hardened and enclosed in Faraday cages. Solid shield cables are solid bonded both to the gage shield and the cable tray. Braided shield cables are bonded to the cable tray and enclosed in solid conduit which is bonded both to the gage shield and the cable trays. There were some cables which were inherently noisy due to proximity to the working point, for example, the A&F cables and zero room wall gages, or carried strong signals such as the Reaction History (data signal) or the pipe expansion cables (driver signals). These required special treatment and were handled as follows: The A&F cables and the zero room wall gage cables and Reaction History cables were run in a separate 18" x 6" tray in the auxiliary drift with the A&F cables separated from all others by 6" concrete spacers. These trays were then fully grouted to enhance bleeding noise signals off these shields and to ensure that this noise source was separated from the signal cables per se. Additionally, one driver cable for the pipe expansion gage was included in this tray. In the main drift, only the pipe expansion driver cables were affected and these were run in separate conduits to the gages. All these cables rejoined the main signal cable bundles at the portal side of the tray ends.

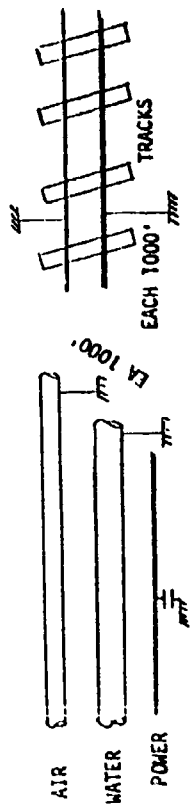
The limited number of cables that do not admit of such treatment due to the nature of the experiment, e.g., FCTC thermocouple wire, were positioned as far as possible from all other gages and cables to minimize their effect on the main cable plant. Slifers and other exposed cables were EM shielded at the working point end.

D. Bleed-off Shield Noise

Conductive powder/resin areas at the portal end of each cable tray assured good contact between all shields and their respective cable tray. Originally, micron size copper powder was planned for this purpose but proved unsatisfactory due to apparent oxidation of the copper with a resultant unacceptably high resistance. The combination of lead shot/conductive resin provided useable conductivity ($\sim .1$ ohm to ground) with the remaining volume of the trays back filled with grout to make the tray as lossy as possible. Trays were originally planned to be rock bolt grounded at 20 foot intervals but this requirement was deleted since the grout conductivity was considered to be high enough to provide an essentially continuous ground. Wire mesh curtains perpendicular to the tray axes, were installed at the portal end of each tray to assure positive grounding of the trays to the drift boundaries. Grounding of each cable shield at the alcove and mesa splice racks was originally planned, but these requirements were deleted since they represented a major modification to the existing cable plant. All cable runs from both drifts were routed through lead shot/conductive resin pits prior to entering and after exiting the instrumentation alcoves. Cables that did not originate in the drifts passed through one or both of these pits depending on their point of origin. All cables were grounded to unistruts at the Overburden Plug. Cable shields were bonded to the feed through on the instrumentation trailers. Efforts were made to render the trailers as Electro-magnetic Interference (EMI) tight as possible; such items included removal of all unnecessary wiring penetrations, conductive covering of all holes, and emphasis on RF power filters and door gasket integrity.

E. Common Node Residual Noise

The lead shot/conductive resin matrix pits above also served to spread what noise remained over all channels in an attempt to reduce the effect on any one channel.



CABLE LEGEND

--- TOR'S SLIFERS
..... OTHER GAGES
--- REACTION HISTORY
--- ARMING & FIRING
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